IN THE UNITED STATES PATENT AND TRADEMARK OFFICE

In re the application of: **Duelli et al.** Group Art Unit: **2874**

Application Number: **10/098,585**

Filed: **March 15, 2002** Examiner: **WOOD, Kevin S.**

For: **COMPACT OPTICAL FIBER COUPLER**

DECLARATION UNDER 37 CFR 1.131

Commissioner for Patents
P.O. Box 1450
Alexandria, VA 22313-1450

Sir:

City of Santa Rosa
State of California,

I, Andrew T. Taylor, declare that all statements made of my own knowledge are true, and that all statements made on information and belief are believed to be true:

1. I am an applicant of the above-identified patent application and an inventor of the subject matter described and claimed therein.

2. Prior to February 17, 2001, I conceived the idea in the United States, of coupling a compact optical fiber as described and claimed in the application and diligently worked on this idea until it was reduced to practice. All actions noted hereafter took place in the United States.

3. Attached to this declaration and marked as exhibit A is a copy of co-inventor and co-applicant, Markus Duelli's, lab notes showing coupling configurations for the claimed fiber optic coupling assembly with distances L > 220 micrometer and diameters d < 30 micrometer. The lab notes are dated from March 29, 2000 to April 10, 2000. By the latter date, Markus Duelli had determined the preferred working distance (L) and diameters (d) as claimed. From the date of March 29, 2000 onward, my co-applicants and I diligently worked toward reduction to practice of this invention.

4. Attached to this declaration and marked as exhibit B is a copy of my lab notes showing an initial sketch of the claimed invention. The notes are dated May 12, 2000. The notes illustrate essential elements of the claimed invention. What is shown is a fiber optic coupling assembly comprising:

a) a first optical waveguide having a first terminal end,

b) a section of graded index fiber ,

wherein the first terminal end of said graded index fiber is in optical communication with the first terminal end of the first optical waveguide

whereby an optical beam propagating from the first terminal end of the first optical waveguide and exiting the second terminal end of the graded index fiber is reduced to a diameter d at distance from the terminal end of the graded index fiber L, wherein d is less than about 20 microns and L is greater than about 220 microns.

In claim 1 of the instant invention d is defined to be less than about 30 microns and L is greater than about 220 microns. These dimensions correspond to the coupling configurations in Markus Duelli's initial lab notes of March/April 2000.

5. Subsequent calculations to determine the required grin parameter to realize certain working distances and diameters were used to generate the specifications for the custom Grin fiber. On June 16, 2000 Markus Duelli prepared a working paper entitled "Specifications for Custom Grin-Fiber" showing a Custom Multimode Fiber (CMMF) index. Copies of the calculations and a copy of Markus Duelli's working paper dated June 16, 2000, which indicates the specifications for the custom Grin fiber, are enclosed herewith as exhibit C.

6. In a continuous effort to reduce this invention to practice applicants diligently proceeded, and in July of 2000, just shortly after the specifications for the Grin fiber were determined, the fiber tubes required to build a prototype of the claimed invention, were ordered. E-mail correspondence between myself and supplier, FiberCore Jena Gmbh, dated between June 24, 2000 and July 16, 2000 and subsequent proof of delivery dated September 15, 2000, are attached herewith as exhibit D.

7. Attached as exhibit E is a copy of co-applicant and co-inventor, Leland Black's lab notes detailing the test results with commercial multimode fiber. The lab notes are dated July 31, 2000.

8. **In September 2000 the invention was reduced to practice when prototypes of the invention were built and tested.** A copy of my lab notes dated September 21, 2000, detailing the first measurements of spot size (diameter d) for different grin lengths of the first prototypes built, are attached herewith as exhibit F.

9. Between September 28, 2000 and January 2, 2001, applicants developed the cleave process with CMMF and optimized the assembly process. Lab Notes by Leland Black, co-applicant and co-inventor, Bob Hallock, and myself, dated September 28, 2000, November 13, 2000 and January 2, 2001, detailing the design and testing are attached herewith as exhibit G.

10. Attached to this declaration and marked as exhibit H, is a copy of an e-mail dated November 15, 2000 from Leland Black to Bob Hallock and attached files, detailing the manufacturing process and optical performance of the MEMS Optical Sub-Assembly, and the current optical assembly process.

11. Applicants demonstrated due diligence by filing a provisional patent application for the claimed invention on March 16, 2001.

12. Because of the extensive effort required to develop a functioning prototype of the claimed invention, it is believed that no undue delay occurred.

13. I acknowledge that willful false statements and the like are punishable by fine and/or imprisonment, and may jeopardize the validity of the application or any patent issuing therefrom.

Sworn at the city of Santa Rosa in the State of California, this twenty-fourth day of March, 2004

Andrew T. Taylor
Andrew T. Taylor

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Markus Duelli
Markus Duelli

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Sworn at the city of Santa Rosa in the
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March, 2004

Leland Black

OCLI

PROJECT NO.

TITLE BOOK NO.

Work continued from Page

maximum reasonable core-radius for current switch design:

$r \simeq 12\,\mu m$ (beam diameter = $24\,\mu m$)

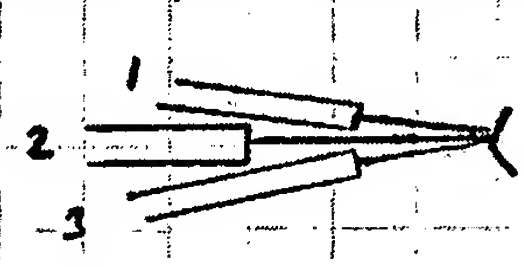
for -0.3 dB insertion loss ⇒ working distance = $156\,\mu m$
distance to mirror = $78\,\mu m$

⇒ 77° between fibers (more than for lensed fibers!)

for -0.5 dB insertion loss ⇒ working distance = $200\,\mu m$
distance to mirror = $100\,\mu m$
64° degrees between fibers (no tolerance!)

⇒ for 2×2 switch TEC-fibers not feasable.

possible solution for 1×2 switch:



asymmetric set-up

z.B.: 90° between fiber 1-3 and min. distance $30\,\mu m$

dist to mirror = $84\,\mu m$ ⇒ dist to fiber 2 has to be
$156 - 84\,\mu m = 72\,\mu m$!

not possible!



Work continued to Page

SIGNATURE Markus Duelli DATE 3/29/2000

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Work continued from Page

using lensed fibers we need 140° between fiber 1-3. Can we do better with TEC-fibers?

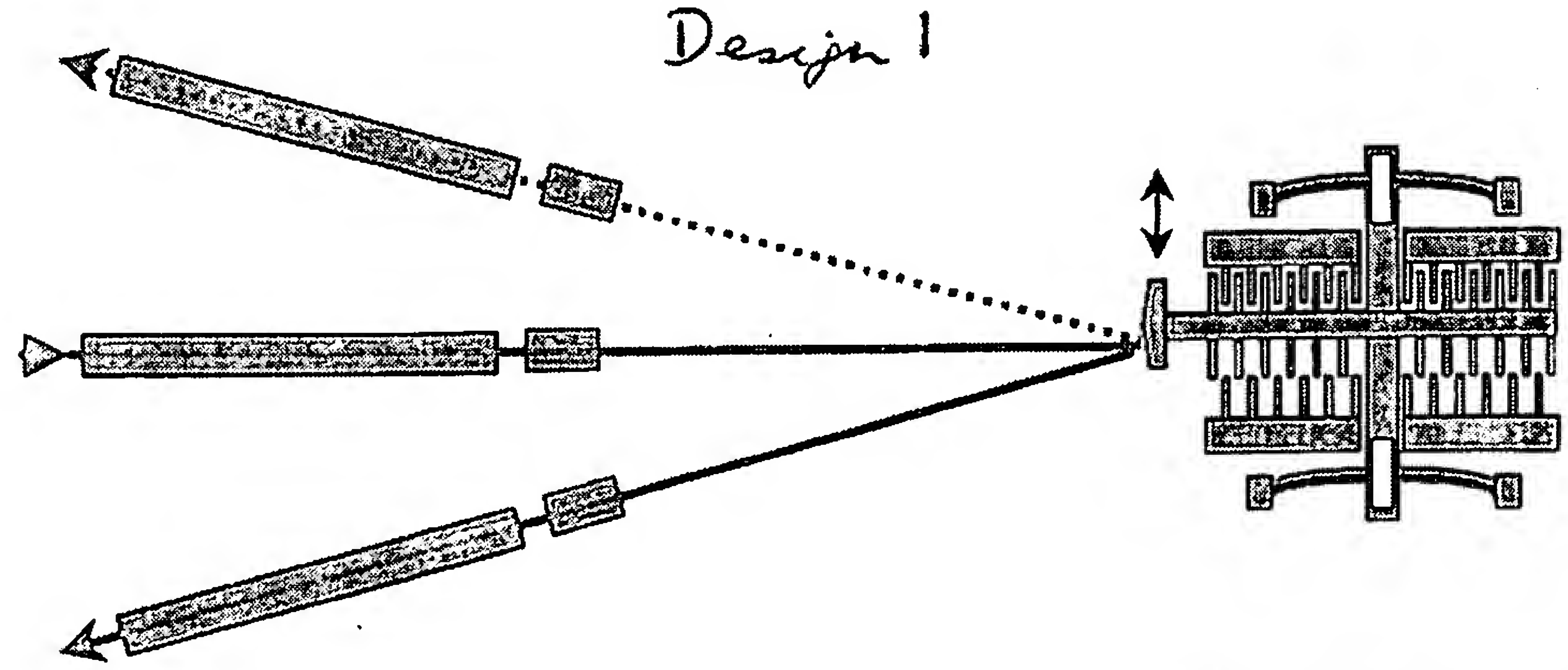
140° between 1-3 ⇒ distance to mirror = 39 μm
distance mirror - fiber 2 = 117 μm
for 117 μm we need an ~~distance of~~ angle of 60° between fibers 1-2

⇒ TEC fibers with r = 12 μm would allow a slightly better (closer) angle between the fibers.

concerns with TEC-fibers: - core size tolerance
- AR-coating
- return loss! → angle polishing?

Possible 1x2 configuration:

Design 1



Work continued to Page

SIGNATURE Markus Duelli DATE 3/30/2000

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Work continued from Page

- main concern in this set-up: lateral movement of the beam during switching - ringing

calculations for Gradissimo - fibers:

spot size on mirror : 15 μm
⇒ maximum working distance (spot size on grad-lens ≤ 80 μm) = 1200 μm
⇒ ~~maximum~~ minimum angle between fibers (with 10 μm distance between neighbouring fibers): 6.5°

⇒ choose the following parameters:

- angle between fibers : 10°
⇒ input angle on mirror 5° (⇒ PDL neglectable)
- working distance : 800 μm
- fiber - to - fiber distance : 1500 μm

⇒ gradissimo parameters :

- spot size : 15 μm
- working distance : ~~800 μm~~ 800 μm
(beam size on Grin lens : ~~49.9~~ 53.2 μm)
radius!

Work continued to Page

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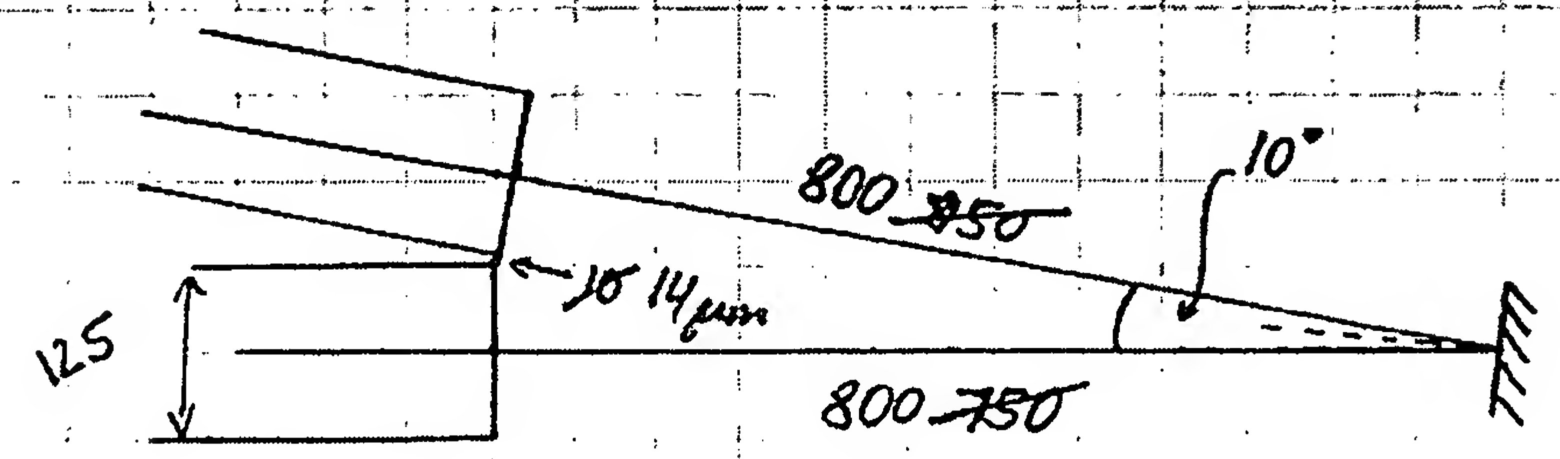
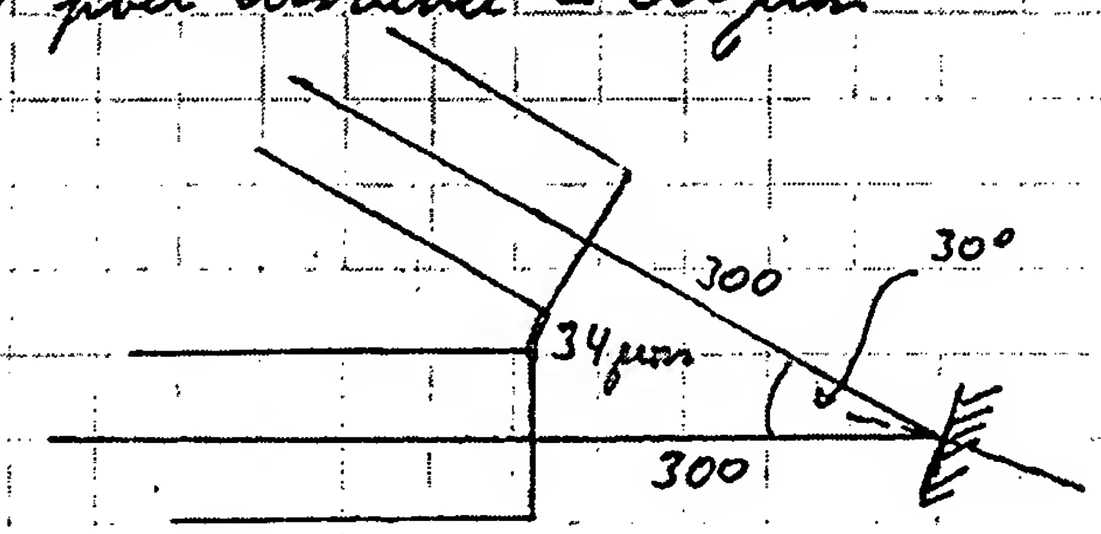



incidence angle on mirror: 5°, $PDL_{theory} \leq 1 \cdot 10^{-3} = (7.7 \times 10^{-4}\,dB)$

or define maximum PDL < 0.01 dB

⇒ $\alpha = 30°$, PDL = 0.007 dB (incidence angle on mirror = 15°)
working distance > 254 µm

⇒ set working distance = 300 µm
fiber-to-fiber distance = 600 µm




Gradissimo to aquire for this design:

working distance: 300µm, spot size: ≤ 15 µm

Work continued to Page

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PROJECT NO.

TITLE

BOOK NO.

Work continued from Page

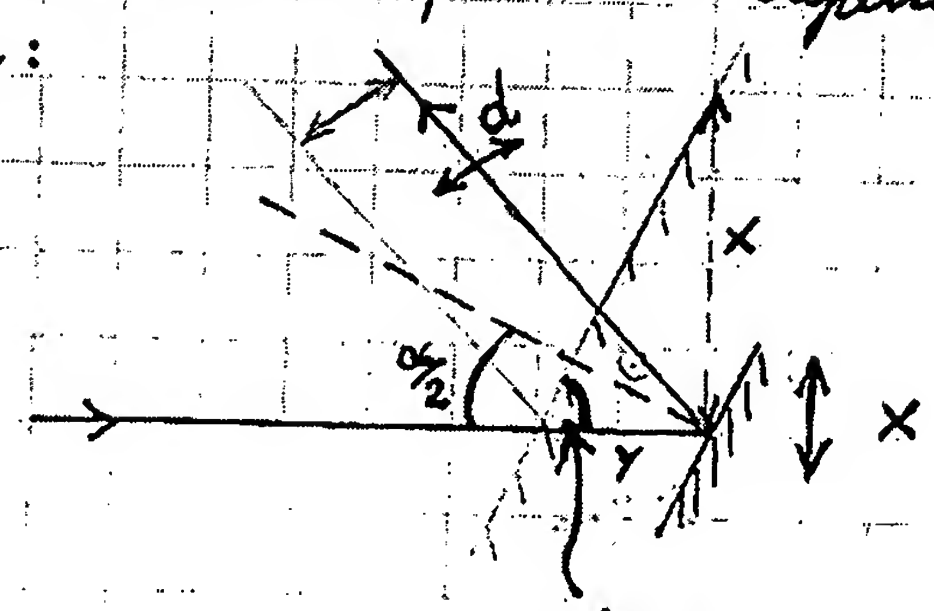
Concerns with Gradissimo fibers:

- availability (one supplier)
- prize
- OCLI has to do the AR-coating
- Return loss

to get return loss to -40-50 dB OCLI has to angle polish (8°) and AR-coat the fibers.

Additional considerations for design 1: (page 51)

lateral movement of beam dependent on mirror position:




$90° - \alpha/2 \Rightarrow Y = x / tg(90° - \alpha/2)$

$$\Rightarrow d = Y \cdot \sin\alpha = \frac{x}{tg(90° - \alpha/2)} \cdot \sin\alpha$$

Work continued to Page

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DATE

WITNESS

DATE

e.g.: $x = \pm 10\,\mu m$ , $\alpha = 30°$ ⇒ $d = \pm 1.34\,\mu m$

$\alpha = 10°$ ⇒ $d = \pm 0.152\,\mu m$

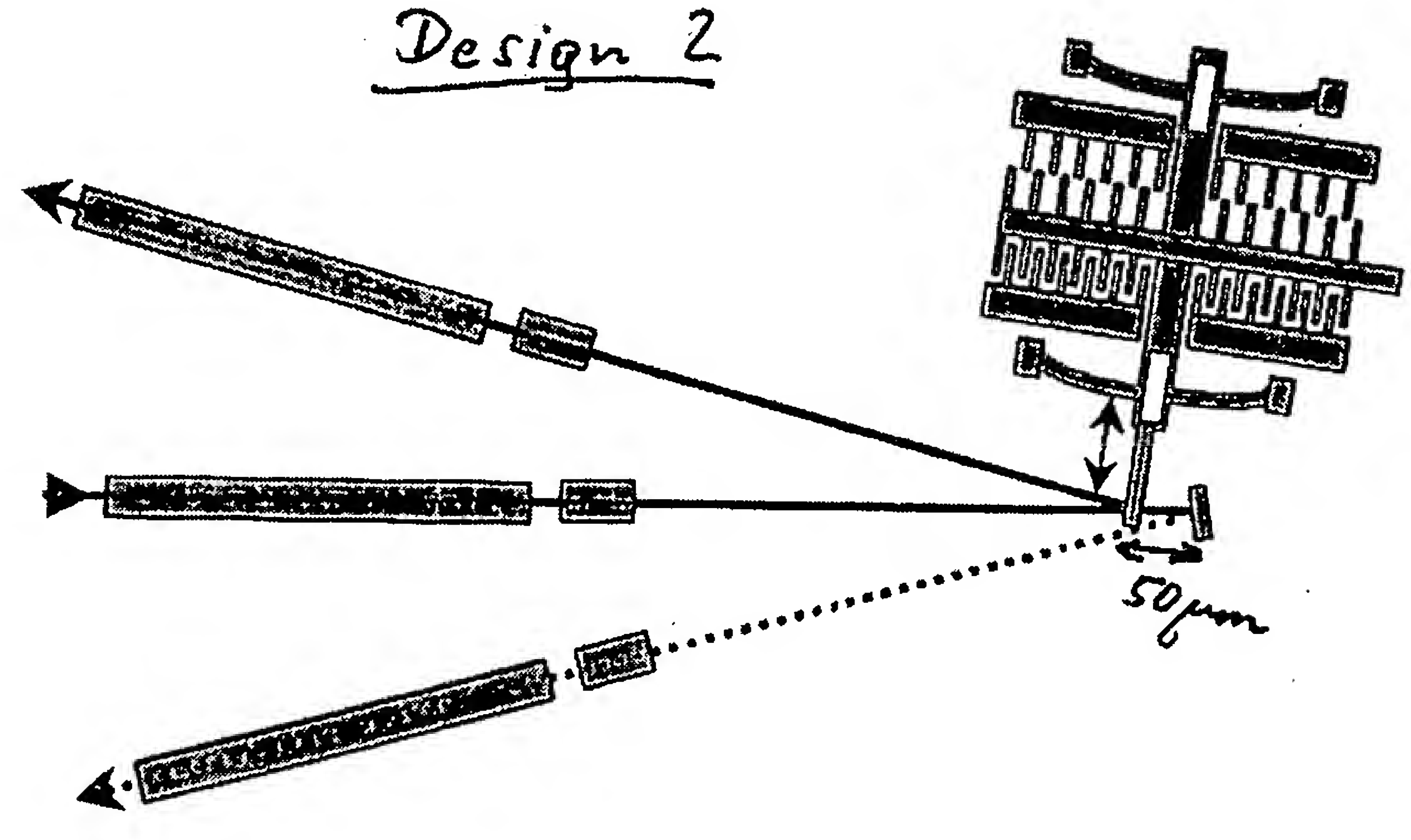
⇒ for small angles this movement is not of great concern.

$d = 0.15\,\mu m$ causes an additional loss of 0.02 dB for cleaved fibers.

for $d = 1.5\,\mu m$ this loss increases to 0.17 dB!

However, this sideways motion of the beam can be avoided by using Design 2:

Design 2

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OCLI

PROJECT NO.

TITLE

BOOK NO.

Work continued from page

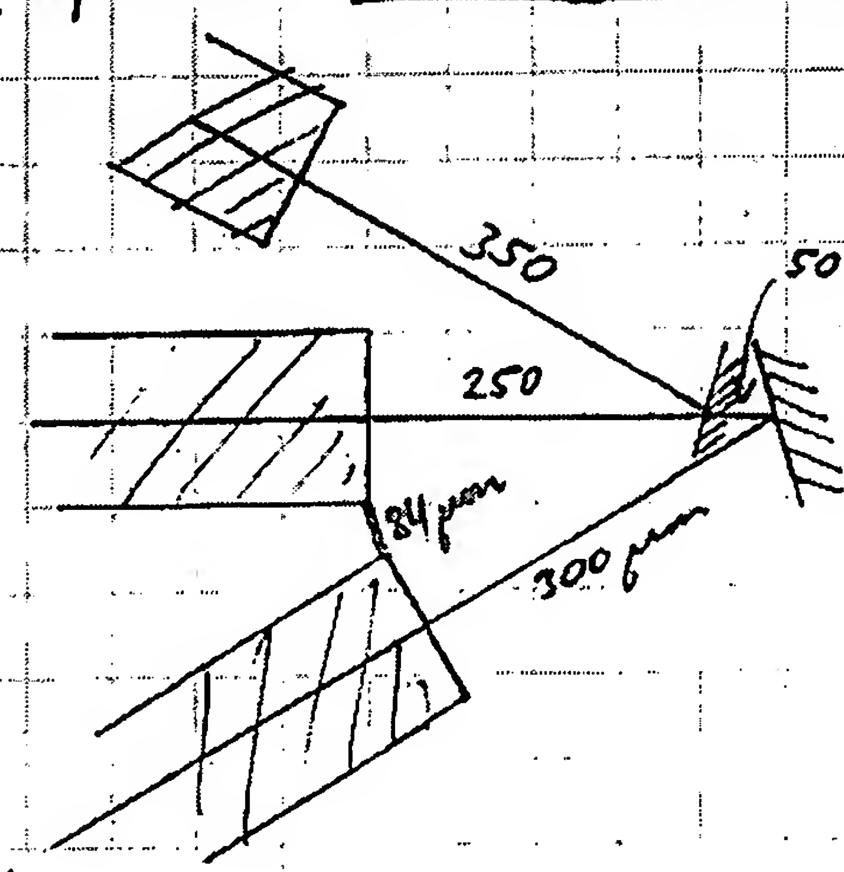
Geometric limitations:

beam size 15 µm ⇒ static mirror size: 30 µm
equals size of moving mirror

save distance between moving and static mirror: 50 µm
(according to Mingao)

a) angle between fibers: 30°, PDL (theoretical) = 0.007 dB

focus of beam between the two mirrors;




beam waist on mirror:
15.2 µm

beam waist on grad-lens:
42.2 µm

Gradissimo specs: beam waist at focus = ~~10~~ 15 µm
working distance 300 µm

expected loss with standard gradissimo fibers: < 1 dB including
Fresnel losses



Work continued to Page

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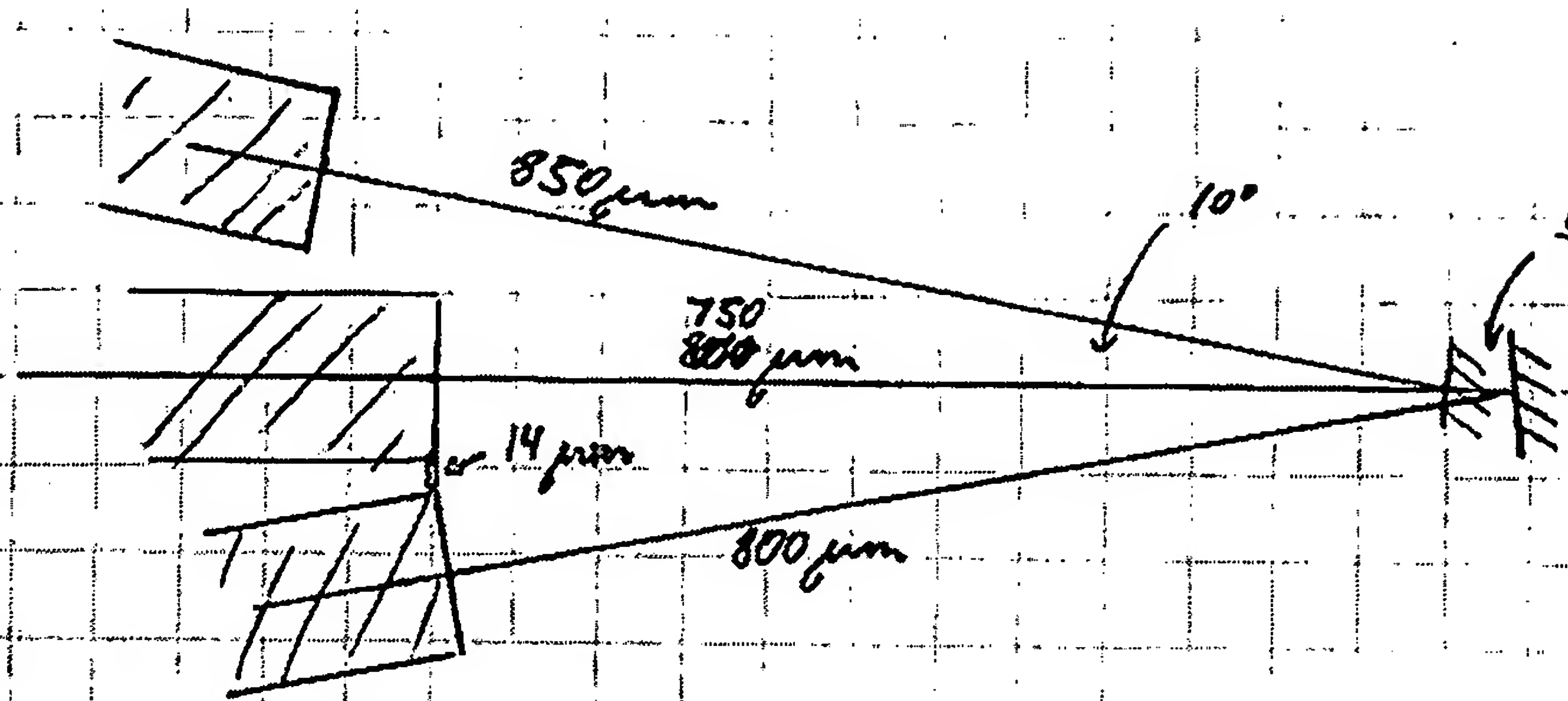
WITNESSED AND UNDERSTOOD BY | DATE | WITNESS | DATE

b) angle between fibers 10°  PDL < $1 \cdot 10^{-3}$
focus in between the two mirrors




beam waist on mirrors: 15.2 µm
beam waist at focus: ~~18 µm~~ 15 µm
beam waist at grin-lens: 106 µm

too big, should be ≤ 60% of grin diameter

⇒ beam waist on mirrors: 22.1 µm
beam waist at focus: 22 µm
beam waist at grin lens: 75 µm

working distance: 800 µm

estimated insertion loss for standard Gradiums: < 1 dB including Fresnel losses

Work continued to Page

Markus Duelli

4/10/2000

TITLE

BOOK NO.

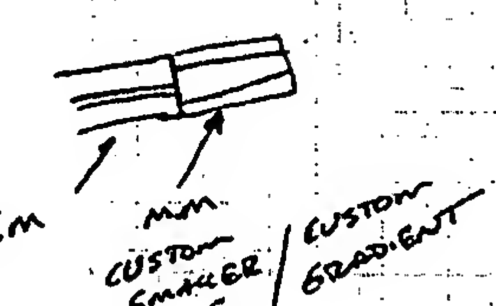
→ m/ACTIVES/MEMS

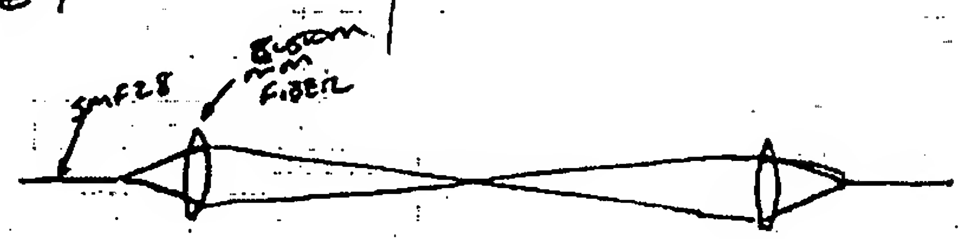
ACCESS

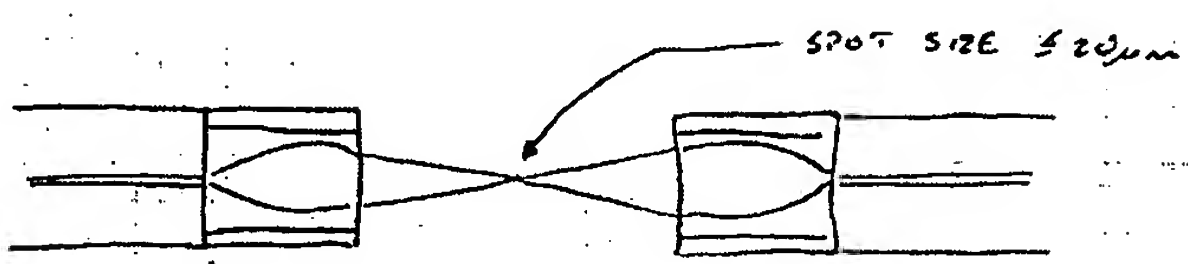
w/ BARBARA

DON F
CHRIS T
MARKUS D
CRAIG O
MINYAO O
ANTHONY M
LARRY M
BRYANT H
&
BOB H's GROUP

ANDREW F.
OPTIC IDEA




→ TO REDUCE I.L. (WHICH WOULD CAUSE R.L.) INDEX OF GRADED INDEX M.M. FIBER MUST MATCH @ SMF28 CORE AREA.

→ GERMANIUM TO RAISE n / FLOURINE TO LOWER n

→ BEND RADIUS
VS. OPTICAL LOSS
20mm R. VS 10mm R
(TINO)

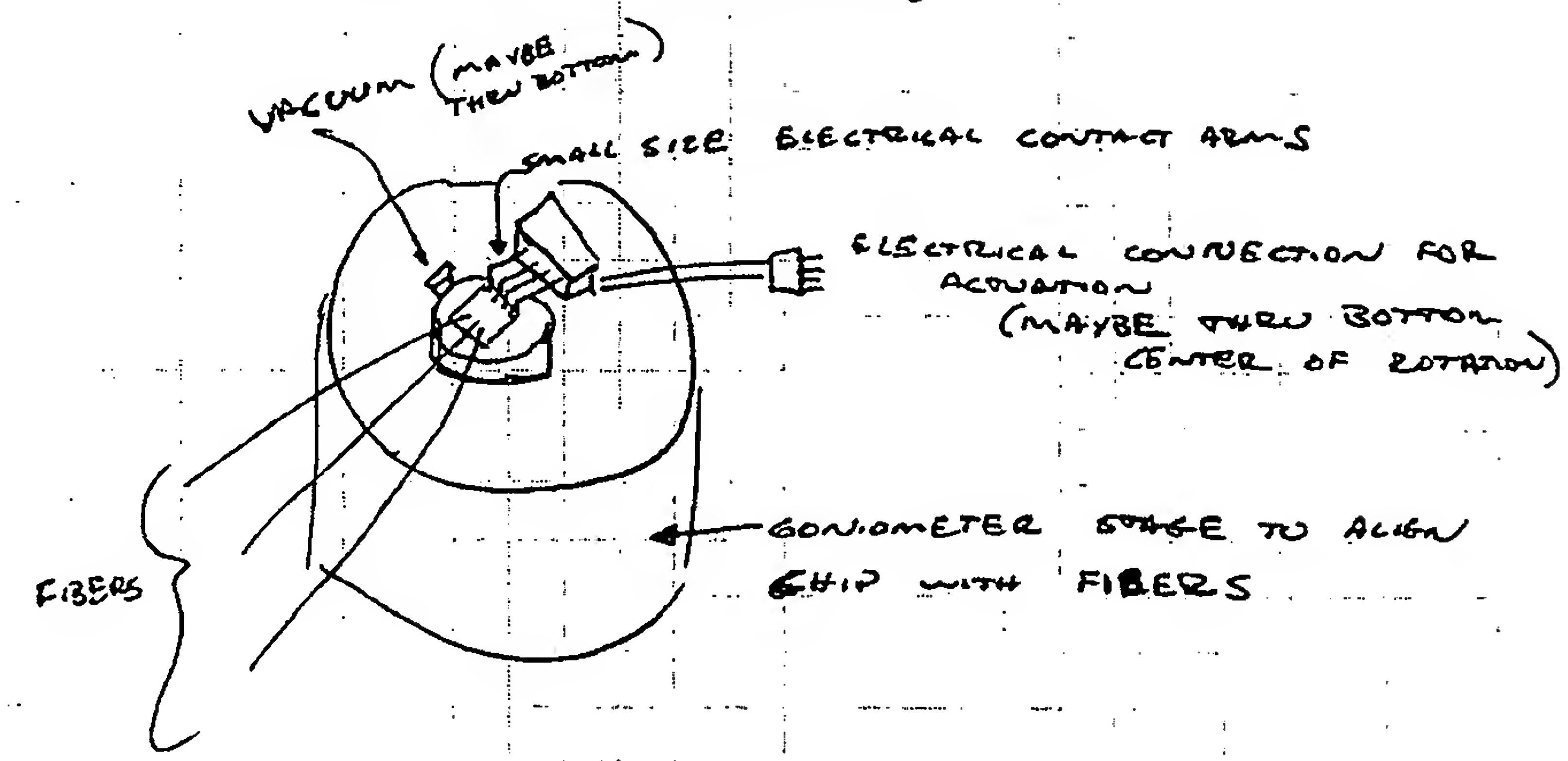
→ SMF28 / FUSED SILICA / GRIN FIBER

↑
GRADISSIMO FIBER
→ ~2 μm TOLERANCE

→ FOWARD JDSU TRIP REPORT TO RICK R.

Work continued from Page

MEMS TOOLING






Work continued to Page

SIGNATURE

DATE 5/12/00

DISCLOSED TO AND UNDERSTOOD BY

DATE

WITNESS

DATE

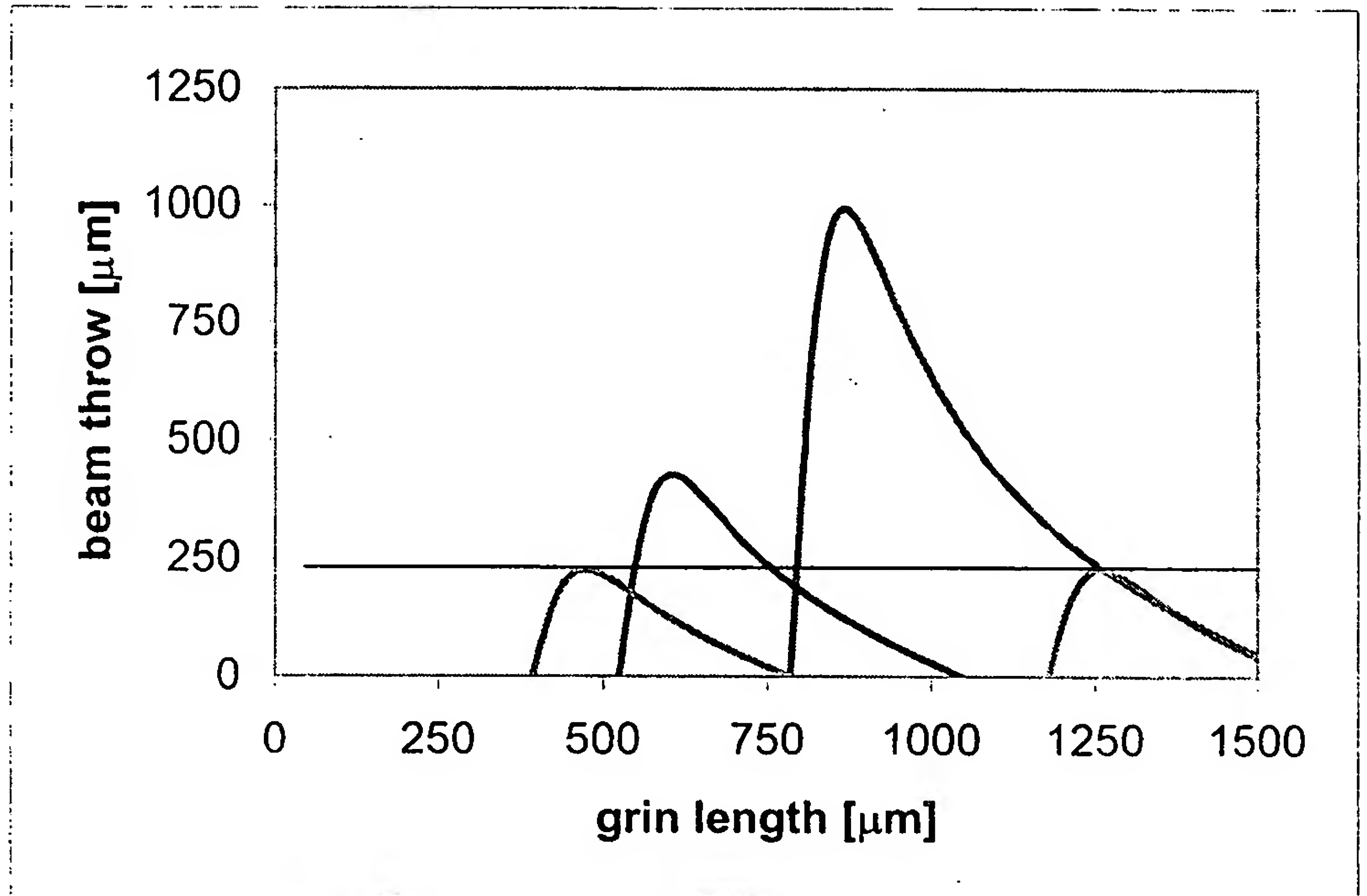
| no. | x | grin length [um] | beam throw [um] g = 2mm^-1 | g = 3mm^-1 | g = 4 mm^-1 | y01 | y01 | y01 | spot size [um] g = 2mm^-1 | g = 3mm^-1 |
|---|---|---|---|---|---|---|---|---|---|---|
| 1 | 1.00E-03 | 10.00 | -6.57 | -6.34 | -6.02 | -6.57E-04 | -6.34E-04 | -6.02E-04 | 10.57 | 10.57 |
| 2 | 2.00E-03 | 20.00 | -13.15 | -12.69 | -12.05 | -1.32E-03 | -1.27E-03 | -1.21E-03 | 10.57 | 10.58 |
| 3 | 3.00E-03 | 30.00 | -19.74 | -19.07 | -18.11 | -1.97E-03 | -1.91E-03 | -1.81E-03 | 10.58 | 10.61 |
| 4 | 4.00E-03 | 40.00 | -26.34 | -25.46 | -24.21 | -2.63E-03 | -2.55E-03 | -2.42E-03 | 10.60 | 10.64 |
| 5 | 5.00E-03 | 50.00 | -32.96 | -31.90 | -30.36 | -3.30E-03 | -3.19E-03 | -3.04E-03 | 10.62 | 10.68 |
| 6 | 6.00E-03 | 60.00 | -39.61 | -38.38 | -36.58 | -3.96E-03 | -3.84E-03 | -3.66E-03 | 10.64 | 10.73 |
| 7 | 7.00E-03 | 70.00 | -46.28 | -44.93 | -42.87 | -4.63E-03 | -4.49E-03 | -4.29E-03 | 10.67 | 10.79 |
| 8 | 8.00E-03 | 80.00 | -52.99 | -51.54 | -49.26 | -5.30E-03 | -5.15E-03 | -4.93E-03 | 10.70 | 10.86 |
| 9 | 9.00E-03 | 90.00 | -59.74 | -58.22 | -55.76 | -5.97E-03 | -5.82E-03 | -5.58E-03 | 10.73 | 10.94 |
| 10 | 1.00E-02 | 100.00 | -66.54 | -65.00 | -62.39 | -6.65E-03 | -6.50E-03 | -6.24E-03 | 10.77 | 11.03 |
| 11 | 1.10E-02 | 110.00 | -73.38 | -71.88 | -69.15 | -7.34E-03 | -7.19E-03 | -6.91E-03 | 10.82 | 11.13 |
| 12 | 1.20E-02 | 120.00 | -80.28 | -78.87 | -76.07 | -8.03E-03 | -7.89E-03 | -7.61E-03 | 10.87 | 11.25 |
| 13 | 1.30E-02 | 130.00 | -87.25 | -85.99 | -83.16 | -8.72E-03 | -8.60E-03 | -8.32E-03 | 10.92 | 11.37 |
| 14 | 1.40E-02 | 140.00 | -94.28 | -93.25 | -90.43 | -9.43E-03 | -9.32E-03 | -9.04E-03 | 10.98 | 11.51 |
| 15 | 1.50E-02 | 150.00 | -101.38 | -100.66 | -97.91 | -1.01E-02 | -1.01E-02 | -9.79E-03 | 11.05 | 11.66 |
| 16 | 1.60E-02 | 160.00 | -108.57 | -108.24 | -105.61 | -1.09E-02 | -1.08E-02 | -1.06E-02 | 11.12 | 11.82 |
| 17 | 1.70E-02 | 170.00 | -115.84 | -116.00 | -113.54 | -1.16E-02 | -1.16E-02 | -1.14E-02 | 11.19 | 12.00 |
| 18 | 1.80E-02 | 180.00 | -123.21 | -123.96 | -121.71 | -1.23E-02 | -1.24E-02 | -1.22E-02 | 11.27 | 12.20 |
| 19 | 1.90E-02 | 190.00 | -130.68 | -132.14 | -130.13 | -1.31E-02 | -1.32E-02 | -1.30E-02 | 11.35 | 12.41 |
| 20 | 2.00E-02 | 200.00 | -138.25 | -140.56 | -138.81 | -1.38E-02 | -1.41E-02 | -1.39E-02 | 11.45 | 12.64 |
| 21 | 2.10E-02 | 210.00 | -145.95 | -149.23 | -147.73 | -1.46E-02 | -1.49E-02 | -1.48E-02 | 11.54 | 12.89 |
| 22 | 2.20E-02 | 220.00 | -153.77 | -158.18 | -156.88 | -1.54E-02 | -1.58E-02 | -1.57E-02 | 11.65 | 13.16 |
| 23 | 2.30E-02 | 230.00 | -161.72 | -167.43 | -166.22 | -1.62E-02 | -1.67E-02 | -1.66E-02 | 11.76 | 13.45 |
| 24 | 2.40E-02 | 240.00 | -169.81 | -177.01 | -175.68 | -1.70E-02 | -1.77E-02 | -1.76E-02 | 11.87 | 13.76 |
| 25 | 2.50E-02 | 250.00 | -178.06 | -186.93 | -185.18 | -1.78E-02 | -1.87E-02 | -1.85E-02 | 12.00 | 14.10 |
| 26 | 2.60E-02 | 260.00 | -186.47 | -197.22 | -194.54 | -1.86E-02 | -1.97E-02 | -1.95E-02 | 12.13 | 14.47 |
| 27 | 2.70E-02 | 270.00 | -195.06 | -207.92 | -203.56 | -1.95E-02 | -2.08E-02 | -2.04E-02 | 12.26 | 14.87 |
| 28 | 2.80E-02 | 280.00 | -203.83 | -219.04 | -211.89 | -2.04E-02 | -2.19E-02 | -2.12E-02 | 12.41 | 15.30 |
| 29 | 2.90E-02 | 290.00 | -212.79 | -230.61 | -219.09 | -2.13E-02 | -2.31E-02 | -2.19E-02 | 12.57 | 15.76 |
| 30 | 3.00E-02 | 300.00 | -221.97 | -242.65 | -224.51 | -2.22E-02 | -2.43E-02 | -2.25E-02 | 12.73 | 16.27 |
| 31 | 3.10E-02 | 310.00 | -231.37 | -255.19 | -227.29 | -2.31E-02 | -2.55E-02 | -2.27E-02 | 12.90 | 16.82 |
| 32 | 3.20E-02 | 320.00 | -241.00 | -268.24 | -226.32 | -2.41E-02 | -2.68E-02 | -2.26E-02 | 13.08 | 17.41 |
| 33 | 3.30E-02 | 330.00 | -250.90 | -281.81 | -220.23 | -2.51E-02 | -2.82E-02 | -2.20E-02 | 13.28 | 18.05 |
| 34 | 3.40E-02 | 340.00 | -261.06 | -295.88 | -207.47 | -2.61E-02 | -2.96E-02 | -2.07E-02 | 13.48 | 18.74 |
| 35 | 3.50E-02 | 350.00 | -271.51 | -310.44 | -186.51 | -2.72E-02 | -3.10E-02 | -1.87E-02 | 13.70 | 19.49 |
| 36 | 3.60E-02 | 360.00 | -282.27 | -325.42 | -156.22 | -2.82E-02 | -3.25E-02 | -1.56E-02 | 13.92 | 20.29 |
| 37 | 3.70E-02 | 370.00 | -293.35 | -340.71 | -116.41 | -2.93E-02 | -3.41E-02 | -1.16E-02 | 14.16 | 21.14 |
| 38 | 3.80E-02 | 380.00 | -304.79 | -356.17 | -68.32 | -3.05E-02 | -3.56E-02 | -6.83E-03 | 14.42 | 22.19 |
| 39 | 3.90E-02 | 390.00 | -316.60 | -371.52 | -14.84 | -3.17E-02 | -3.72E-02 | -1.48E-03 | 14.69 | 23.37 |

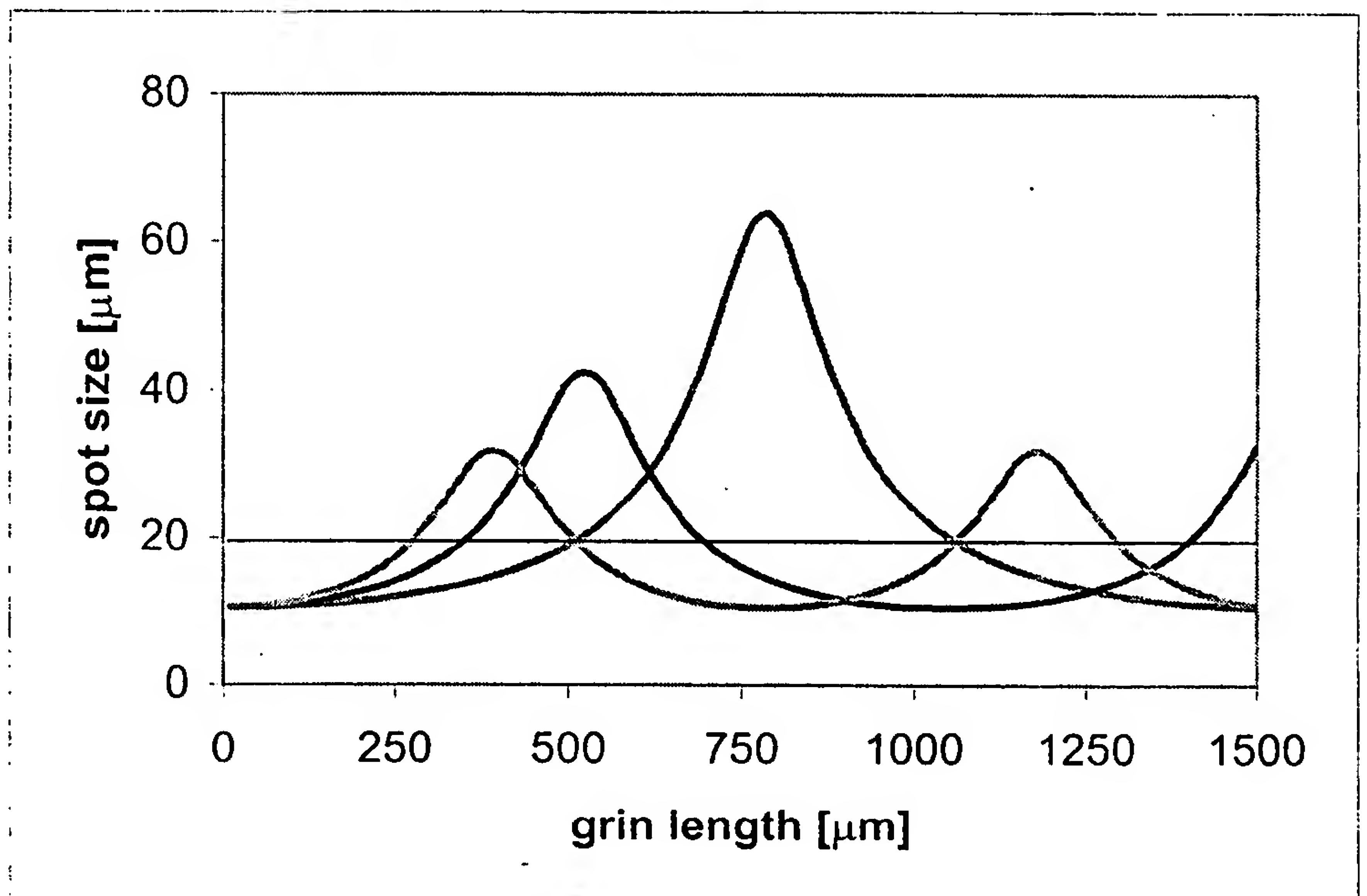
| | | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|
| 40 | 4.00E-02 | 400.00 | -328.81 | -386.40 | 39.87 | -3.29E-02 | -3.86E-02 | 3.99E-03 | 14.97 | 24.67 |
| 41 | 4.10E-02 | 410.00 | -341.44 | -400.23 | 91.33 | -3.41E-02 | -4.00E-02 | 9.13E-03 | 15.27 | 26.06 |
| 42 | 4.20E-02 | 420.00 | -354.53 | -412.23 | 135.87 | -3.55E-02 | -4.12E-02 | 1.36E-02 | 15.59 | 27.51 |
| 43 | 4.30E-02 | 430.00 | -368.11 | -421.28 | 171.36 | -3.68E-02 | -4.21E-02 | 1.71E-02 | 15.93 | 28.89 |
| 44 | 4.40E-02 | 440.00 | -382.20 | -425.86 | 197.26 | -3.82E-02 | -4.26E-02 | 1.97E-02 | 16.29 | 30.64 |
| 45 | 4.50E-02 | 450.00 | -396.86 | -423.96 | 214.27 | -3.97E-02 | -4.24E-02 | 2.14E-02 | 16.67 | 32.28 |
| 46 | 4.60E-02 | 460.00 | -412.10 | -413.09 | 223.76 | -4.12E-02 | -4.13E-02 | 2.24E-02 | 17.08 | 34.19 |
| 47 | 4.70E-02 | 470.00 | -427.99 | -390.33 | 227.31 | -4.28E-02 | -3.90E-02 | 2.27E-02 | 17.51 | 36.10 |
| 48 | 4.80E-02 | 480.00 | -444.56 | -352.73 | 226.40 | -4.45E-02 | -3.53E-02 | 2.26E-02 | 17.97 | 37.85 |
| 49 | 4.90E-02 | 490.00 | -461.86 | -297.94 | 222.28 | -4.62E-02 | -2.98E-02 | 2.22E-02 | 18.46 | 39.73 |
| 50 | 5.00E-02 | 500.00 | -479.93 | -225.22 | 215.95 | -4.80E-02 | -2.25E-02 | 2.16E-02 | 18.98 | 41.15 |
| 51 | 5.10E-02 | 510.00 | -498.85 | -136.54 | 208.17 | -4.99E-02 | -1.37E-02 | 2.08E-02 | 19.54 | 42.04 |
| 52 | 5.20E-02 | 520.00 | -518.65 | -37.02 | 199.47 | -5.19E-02 | -3.70E-03 | 1.99E-02 | 20.14 | 42.42 |
| 53 | 5.30E-02 | 530.00 | -539.40 | 65.59 | 190.26 | -5.39E-02 | 6.56E-03 | 1.90E-02 | 20.79 | 42.36 |
| 54 | 5.40E-02 | 540.00 | -561.16 | 162.76 | 180.81 | -5.61E-02 | 1.63E-02 | 1.81E-02 | 21.47 | 41.84 |
| 55 | 5.50E-02 | 550.00 | -583.98 | 247.35 | 171.32 | -5.84E-02 | 2.47E-02 | 1.71E-02 | 22.21 | 40.81 |
| 56 | 5.60E-02 | 560.00 | -607.92 | 315.11 | 161.90 | -6.08E-02 | 3.15E-02 | 1.62E-02 | 23.01 | 39.25 |
| 57 | 5.70E-02 | 570.00 | -633.04 | 364.92 | 152.64 | -6.33E-02 | 3.65E-02 | 1.53E-02 | 23.86 | 37.25 |
| 58 | 5.80E-02 | 580.00 | -659.37 | 398.08 | 143.59 | -6.59E-02 | 3.98E-02 | 1.44E-02 | 24.78 | 35.60 |
| 59 | 5.90E-02 | 590.00 | -686.94 | 417.20 | 134.78 | -6.87E-02 | 4.17E-02 | 1.35E-02 | 25.77 | 33.61 |
| 60 | 6.00E-02 | 600.00 | -715.73 | 425.28 | 126.22 | -7.16E-02 | 4.25E-02 | 1.26E-02 | 26.84 | 31.82 |
| 61 | 6.10E-02 | 610.00 | -745.71 | 425.13 | 117.92 | -7.46E-02 | 4.25E-02 | 1.18E-02 | 27.98 | 30.05 |
| 62 | 6.20E-02 | 620.00 | -776.76 | 419.12 | 109.86 | -7.77E-02 | 4.19E-02 | 1.10E-02 | 29.20 | 28.53 |
| 63 | 6.30E-02 | 630.00 | -808.69 | 409.11 | 102.04 | -8.09E-02 | 4.09E-02 | 1.02E-02 | 30.55 | 27.10 |
| 64 | 6.40E-02 | 640.00 | -841.17 | 396.50 | 94.44 | -8.41E-02 | 3.96E-02 | 9.44E-03 | 32.18 | 25.66 |
| 65 | 6.50E-02 | 650.00 | -873.68 | 382.30 | 87.06 | -8.74E-02 | 3.82E-02 | 8.71E-03 | 33.96 | 24.29 |
| 66 | 6.60E-02 | 660.00 | -905.43 | 367.25 | 79.87 | -9.05E-02 | 3.67E-02 | 7.99E-03 | 35.91 | 23.03 |
| 67 | 6.70E-02 | 670.00 | -935.26 | 351.83 | 72.86 | -9.35E-02 | 3.52E-02 | 7.29E-03 | 38.00 | 21.88 |
| 68 | 6.80E-02 | 680.00 | -961.48 | 336.40 | 66.02 | -9.61E-02 | 3.36E-02 | 6.60E-03 | 40.19 | 20.89 |
| 69 | 6.90E-02 | 690.00 | -981.73 | 321.18 | 59.32 | -9.82E-02 | 3.21E-02 | 5.93E-03 | 42.32 | 20.06 |
| 70 | 7.00E-02 | 700.00 | -992.71 | 306.31 | 52.76 | -9.93E-02 | 3.06E-02 | 5.28E-03 | 44.90 | 19.27 |
| 71 | 7.10E-02 | 710.00 | -990.05 | 291.89 | 46.31 | -9.90E-02 | 2.92E-02 | 4.63E-03 | 47.49 | 18.54 |
| 72 | 7.20E-02 | 720.00 | -968.15 | 277.95 | 39.96 | -9.68E-02 | 2.78E-02 | 4.00E-03 | 50.34 | 17.86 |
| 73 | 7.30E-02 | 730.00 | -920.36 | 264.53 | 33.71 | -9.20E-02 | 2.65E-02 | 3.37E-03 | 53.34 | 17.24 |
| 74 | 7.40E-02 | 740.00 | -839.61 | 251.63 | 27.52 | -8.40E-02 | 2.52E-02 | 2.75E-03 | 55.97 | 16.66 |
| 75 | 7.50E-02 | 750.00 | -719.83 | 239.23 | 21.40 | -7.20E-02 | 2.39E-02 | 2.14E-03 | 58.97 | 16.12 |
| 76 | 7.60E-02 | 760.00 | -558.20 | 227.32 | 15.32 | -5.58E-02 | 2.27E-02 | 1.53E-03 | 61.31 | 15.63 |
| 77 | 7.70E-02 | 770.00 | -357.79 | 215.88 | 9.27 | -3.58E-02 | 2.16E-02 | 9.27E-04 | 62.84 | 15.17 |
| 78 | 7.80E-02 | 780.00 | -129.20 | 204.88 | 3.25 | -1.29E-02 | 2.05E-02 | 3.25E-04 | 63.57 | 14.75 |
| 79 | 7.90E-02 | 790.00 | 110.27 | 194.30 | -2.77 | 1.10E-02 | 1.94E-02 | -2.77E-04 | 63.86 | 14.36 |
| 80 | 8.00E-02 | 800.00 | 340.43 | 184.11 | -8.79 | 3.40E-02 | 1.84E-02 | -8.79E-04 | 62.92 | 14.00 |
| 81 | 8.10E-02 | 810.00 | 543.57 | 174.29 | -14.84 | 5.44E-02 | 1.74E-02 | -1.48E-03 | 61.46 | 13.67 |
| 82 | 8.20E-02 | 820.00 | 708.49 | 164.81 | -20.91 | 7.08E-02 | 1.65E-02 | -2.09E-03 | 59.18 | 13.36 |

| | | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|
| 83 | 8.30E-02 | 830.00 | 831.57 | 155.64 | -27.03 | 8.32E-02 | 1.56E-02 | -2.70E-03 | 56.22 | 13.08 |
| 84 | 8.40E-02 | 840.00 | 915.23 | 146.77 | -33.21 | 9.15E-02 | 1.47E-02 | -3.32E-03 | 53.56 | 12.82 |
| 85 | 8.50E-02 | 850.00 | 965.39 | 138.17 | -39.46 | 9.65E-02 | 1.38E-02 | -3.95E-03 | 50.59 | 12.57 |
| 86 | 8.60E-02 | 860.00 | 989.09 | 129.83 | -45.80 | 9.89E-02 | 1.30E-02 | -4.58E-03 | 47.69 | 12.35 |
| 87 | 8.70E-02 | 870.00 | 993.07 | 121.71 | -52.24 | 9.93E-02 | 1.22E-02 | -5.22E-03 | 45.15 | 12.14 |
| 88 | 8.80E-02 | 880.00 | 982.99 | 113.80 | -58.79 | 9.83E-02 | 1.14E-02 | -5.88E-03 | 42.48 | 11.95 |
| 89 | 8.90E-02 | 890.00 | 963.35 | 106.09 | -65.48 | 9.63E-02 | 1.06E-02 | -6.55E-03 | 40.37 | 11.78 |
| 90 | 9.00E-02 | 900.00 | 937.50 | 98.56 | -72.31 | 9.38E-02 | 9.86E-03 | -7.23E-03 | 38.17 | 11.62 |
| 91 | 9.10E-02 | 910.00 | 907.89 | 91.20 | -79.31 | 9.08E-02 | 9.12E-03 | -7.93E-03 | 36.07 | 11.47 |
| 92 | 9.20E-02 | 920.00 | 876.25 | 83.98 | -86.48 | 8.76E-02 | 8.40E-03 | -8.65E-03 | 34.11 | 11.33 |
| 93 | 9.30E-02 | 930.00 | 843.77 | 76.90 | -93.85 | 8.44E-02 | 7.69E-03 | -9.38E-03 | 32.32 | 11.21 |
| 94 | 9.40E-02 | 940.00 | 811.27 | 69.94 | -101.43 | 8.11E-02 | 6.99E-03 | -1.01E-02 | 30.68 | 11.10 |
| 95 | 9.50E-02 | 950.00 | 779.28 | 63.09 | -109.23 | 7.79E-02 | 6.31E-03 | -1.09E-02 | 29.30 | 11.00 |
| 96 | 9.60E-02 | 960.00 | 748.14 | 56.34 | -117.27 | 7.48E-02 | 5.63E-03 | -1.17E-02 | 28.07 | 10.92 |
| 97 | 9.70E-02 | 970.00 | 718.07 | 49.68 | -125.55 | 7.18E-02 | 4.97E-03 | -1.26E-02 | 26.93 | 10.84 |
| 98 | 9.80E-02 | 980.00 | 689.18 | 43.09 | -134.09 | 6.89E-02 | 4.31E-03 | -1.34E-02 | 25.86 | 10.77 |
| 99 | 9.90E-02 | 990.00 | 661.52 | 36.56 | -142.88 | 6.62E-02 | 3.66E-03 | -1.43E-02 | 24.86 | 10.71 |
| 100 | 1.00E-01 | 1000.00 | 635.09 | 30.09 | -151.91 | 6.35E-02 | 3.01E-03 | -1.52E-02 | 23.93 | 10.67 |
| 101 | 1.01E-01 | 1010.00 | 609.88 | 23.67 | -161.16 | 6.10E-02 | 2.37E-03 | -1.61E-02 | 23.07 | 10.63 |
| 102 | 1.02E-01 | 1020.00 | 585.84 | 17.28 | -170.56 | 5.86E-02 | 1.73E-03 | -1.71E-02 | 22.27 | 10.60 |
| 103 | 1.03E-01 | 1030.00 | 562.93 | 10.91 | -180.06 | 5.63E-02 | 1.09E-03 | -1.80E-02 | 21.53 | 10.58 |
| 104 | 1.04E-01 | 1040.00 | 541.09 | 4.56 | -189.51 | 5.41E-02 | 4.56E-04 | -1.90E-02 | 20.84 | 10.57 |
| 105 | 1.05E-01 | 1050.00 | 520.27 | -1.78 | -198.75 | 5.20E-02 | -1.78E-04 | -1.99E-02 | 20.19 | 10.57 |
| 106 | 1.06E-01 | 1060.00 | 500.39 | -8.12 | -207.50 | 5.00E-02 | -8.12E-04 | -2.08E-02 | 19.59 | 10.57 |
| 107 | 1.07E-01 | 1070.00 | 481.41 | -14.48 | -215.38 | 4.81E-02 | -1.45E-03 | -2.15E-02 | 19.03 | 10.59 |
| 108 | 1.08E-01 | 1080.00 | 463.27 | -20.86 | -221.85 | 4.63E-02 | -2.09E-03 | -2.22E-02 | 18.50 | 10.61 |
| 109 | 1.09E-01 | 1090.00 | 445.91 | -27.26 | -226.18 | 4.46E-02 | -2.73E-03 | -2.26E-02 | 18.01 | 10.65 |
| 110 | 1.10E-01 | 1100.00 | 429.28 | -33.71 | -227.39 | 4.29E-02 | -3.37E-03 | -2.27E-02 | 17.55 | 10.69 |
| 111 | 1.11E-01 | 1110.00 | 413.35 | -40.21 | -224.24 | 4.13E-02 | -4.02E-03 | -2.24E-02 | 17.11 | 10.74 |
| 112 | 1.12E-01 | 1120.00 | 398.05 | -46.77 | -215.28 | 3.98E-02 | -4.68E-03 | -2.15E-02 | 16.70 | 10.81 |
| 113 | 1.13E-01 | 1130.00 | 383.35 | -53.40 | -198.93 | 3.83E-02 | -5.34E-03 | -1.99E-02 | 16.32 | 10.88 |
| 114 | 1.14E-01 | 1140.00 | 369.21 | -60.11 | -173.77 | 3.69E-02 | -6.01E-03 | -1.74E-02 | 15.96 | 10.96 |
| 115 | 1.15E-01 | 1150.00 | 355.59 | -66.92 | -139.05 | 3.56E-02 | -6.69E-03 | -1.39E-02 | 15.62 | 11.06 |
| 116 | 1.16E-01 | 1160.00 | 342.47 | -73.83 | -95.17 | 3.42E-02 | -7.38E-03 | -9.52E-03 | 15.30 | 11.16 |
| 117 | 1.17E-01 | 1170.00 | 329.80 | -80.85 | -44.14 | 3.30E-02 | -8.09E-03 | -4.41E-03 | 14.99 | 11.28 |
| 118 | 1.18E-01 | 1180.00 | 317.56 | -88.01 | 10.46 | 3.18E-02 | -8.80E-03 | 1.05E-03 | 14.71 | 11.41 |
| 119 | 1.19E-01 | 1190.00 | 305.72 | -95.31 | 64.21 | 3.06E-02 | -9.53E-03 | 6.42E-03 | 14.44 | 11.55 |
| 120 | 1.20E-01 | 1200.00 | 294.25 | -102.76 | 112.86 | 2.94E-02 | -1.03E-02 | 1.13E-02 | 14.18 | 11.70 |
| 121 | 1.21E-01 | 1210.00 | 283.14 | -110.39 | 153.40 | 2.83E-02 | -1.10E-02 | 1.53E-02 | 13.94 | 11.87 |
| 122 | 1.22E-01 | 1220.00 | 272.35 | -118.21 | 184.45 | 2.72E-02 | -1.18E-02 | 1.84E-02 | 13.71 | 12.06 |
| 123 | 1.23E-01 | 1230.00 | 261.88 | -126.23 | 206.12 | 2.62E-02 | -1.26E-02 | 2.06E-02 | 13.50 | 12.26 |
| 124 | 1.24E-01 | 1240.00 | 251.70 | -134.47 | 219.48 | 2.52E-02 | -1.34E-02 | 2.19E-02 | 13.29 | 12.47 |
| 125 | 1.25E-01 | 1250.00 | 241.78 | -142.96 | 226.04 | 2.42E-02 | -1.43E-02 | 2.26E-02 | 13.10 | 12.71 |

| | | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|
| 126 | 1.26E-01 | 1260.00 | 232.12 | -151.71 | 227.36 | 2.32E-02 | -1.52E-02 | 2.27E-02 | 12.92 | 12.96 |
| 127 | 1.27E-01 | 1270.00 | 222.71 | -160.74 | 224.84 | 2.23E-02 | -1.61E-02 | 2.25E-02 | 12.74 | 13.23 |
| 128 | 1.28E-01 | 1280.00 | 213.51 | -170.08 | 219.59 | 2.14E-02 | -1.70E-02 | 2.20E-02 | 12.58 | 13.53 |
| 129 | 1.29E-01 | 1290.00 | 204.53 | -179.75 | 212.51 | 2.05E-02 | -1.80E-02 | 2.13E-02 | 12.42 | 13.85 |
| 130 | 1.30E-01 | 1300.00 | 195.75 | -189.78 | 204.25 | 1.96E-02 | -1.90E-02 | 2.04E-02 | 12.28 | 14.20 |
| 131 | 1.31E-01 | 1310.00 | 187.15 | -200.18 | 195.28 | 1.87E-02 | -2.00E-02 | 1.95E-02 | 12.14 | 14.58 |
| 132 | 1.32E-01 | 1320.00 | 178.73 | -210.99 | 185.93 | 1.79E-02 | -2.11E-02 | 1.86E-02 | 12.01 | 14.98 |
| 133 | 1.33E-01 | 1330.00 | 170.47 | -222.23 | 176.44 | 1.70E-02 | -2.22E-02 | 1.76E-02 | 11.88 | 15.42 |
| 134 | 1.34E-01 | 1340.00 | 162.36 | -233.93 | 166.97 | 1.62E-02 | -2.34E-02 | 1.67E-02 | 11.76 | 15.90 |
| 135 | 1.35E-01 | 1350.00 | 154.39 | -246.11 | 157.62 | 1.54E-02 | -2.46E-02 | 1.58E-02 | 11.65 | 16.42 |
| 136 | 1.36E-01 | 1360.00 | 146.57 | -258.80 | 148.45 | 1.47E-02 | -2.59E-02 | 1.48E-02 | 11.55 | 16.98 |
| 137 | 1.37E-01 | 1370.00 | 138.86 | -271.99 | 139.51 | 1.39E-02 | -2.72E-02 | 1.40E-02 | 11.45 | 17.58 |
| 138 | 1.38E-01 | 1380.00 | 131.28 | -285.70 | 130.81 | 1.31E-02 | -2.86E-02 | 1.31E-02 | 11.36 | 18.24 |
| 139 | 1.39E-01 | 1390.00 | 123.80 | -299.91 | 122.37 | 1.24E-02 | -3.00E-02 | 1.22E-02 | 11.28 | 18.95 |
| 140 | 1.40E-01 | 1400.00 | 116.42 | -314.60 | 114.18 | 1.16E-02 | -3.15E-02 | 1.14E-02 | 11.20 | 19.71 |
| 141 | 1.41E-01 | 1410.00 | 109.14 | -329.68 | 106.23 | 1.09E-02 | -3.30E-02 | 1.06E-02 | 11.12 | 20.52 |
| 142 | 1.42E-01 | 1420.00 | 101.95 | -345.04 | 98.52 | 1.02E-02 | -3.45E-02 | 9.85E-03 | 11.05 | 21.41 |
| 143 | 1.43E-01 | 1430.00 | 94.84 | -360.49 | 91.02 | 9.48E-03 | -3.60E-02 | 9.10E-03 | 10.99 | 22.51 |
| 144 | 1.44E-01 | 1440.00 | 87.80 | -375.76 | 83.73 | 8.78E-03 | -3.76E-02 | 8.37E-03 | 10.93 | 23.72 |
| 145 | 1.45E-01 | 1450.00 | 80.83 | -390.41 | 76.63 | 8.08E-03 | -3.90E-02 | 7.66E-03 | 10.87 | 25.05 |
| 146 | 1.46E-01 | 1460.00 | 73.93 | -403.82 | 69.69 | 7.39E-03 | -4.04E-02 | 6.97E-03 | 10.82 | 26.46 |
| 147 | 1.47E-01 | 1470.00 | 67.08 | -415.12 | 62.92 | 6.71E-03 | -4.15E-02 | 6.29E-03 | 10.78 | 27.91 |
| 148 | 1.48E-01 | 1480.00 | 60.28 | -423.09 | 56.29 | 6.03E-03 | -4.23E-02 | 5.63E-03 | 10.74 | 29.23 |
| 149 | 1.49E-01 | 1490.00 | 53.53 | -426.08 | 49.78 | 5.35E-03 | -4.26E-02 | 4.98E-03 | 10.70 | 31.04 |
| 150 | 1.50E-01 | 1500.00 | 46.81 | -421.94 | 43.38 | 4.68E-03 | -4.22E-02 | 4.34E-03 | 10.67 | 32.71 |

| g = 4mm^-1 | y02 | y02 | y02 |
|---|---|---|---|
| 10.57 | 1.06E-03 | 1.06E-03 | 1.06E-03 |
| 10.60 | 1.06E-03 | 1.06E-03 | 1.06E-03 |
| 10.63 | 1.06E-03 | 1.06E-03 | 1.06E-03 |
| 10.69 | 1.06E-03 | 1.06E-03 | 1.07E-03 |
| 10.76 | 1.06E-03 | 1.07E-03 | 1.08E-03 |
| 10.85 | 1.06E-03 | 1.07E-03 | 1.08E-03 |
| 10.95 | 1.07E-03 | 1.08E-03 | 1.09E-03 |
| 11.07 | 1.07E-03 | 1.09E-03 | 1.11E-03 |
| 11.21 | 1.07E-03 | 1.09E-03 | 1.12E-03 |
| 11.37 | 1.08E-03 | 1.10E-03 | 1.14E-03 |
| 11.55 | 1.08E-03 | 1.11E-03 | 1.16E-03 |
| 11.76 | 1.09E-03 | 1.12E-03 | 1.18E-03 |
| 11.98 | 1.09E-03 | 1.14E-03 | 1.20E-03 |
| 12.23 | 1.10E-03 | 1.15E-03 | 1.22E-03 |
| 12.51 | 1.10E-03 | 1.17E-03 | 1.25E-03 |
| 12.82 | 1.11E-03 | 1.18E-03 | 1.28E-03 |
| 13.16 | 1.12E-03 | 1.20E-03 | 1.32E-03 |
| 13.53 | 1.13E-03 | 1.22E-03 | 1.35E-03 |
| 13.94 | 1.14E-03 | 1.24E-03 | 1.39E-03 |
| 14.39 | 1.14E-03 | 1.26E-03 | 1.44E-03 |
| 14.88 | 1.15E-03 | 1.29E-03 | 1.49E-03 |
| 15.42 | 1.16E-03 | 1.32E-03 | 1.54E-03 |
| 15.99 | 1.18E-03 | 1.34E-03 | 1.60E-03 |
| 16.61 | 1.19E-03 | 1.38E-03 | 1.66E-03 |
| 17.29 | 1.20E-03 | 1.41E-03 | 1.73E-03 |
| 18.16 | 1.21E-03 | 1.45E-03 | 1.82E-03 |
| 19.11 | 1.23E-03 | 1.49E-03 | 1.91E-03 |
| 20.13 | 1.24E-03 | 1.53E-03 | 2.01E-03 |
| 21.20 | 1.26E-03 | 1.58E-03 | 2.12E-03 |
| 22.22 | 1.27E-03 | 1.63E-03 | 2.22E-03 |
| 23.46 | 1.29E-03 | 1.68E-03 | 2.35E-03 |
| 24.66 | 1.31E-03 | 1.74E-03 | 2.47E-03 |
| 26.05 | 1.33E-03 | 1.80E-03 | 2.60E-03 |
| 27.41 | 1.35E-03 | 1.87E-03 | 2.74E-03 |
| 28.68 | 1.37E-03 | 1.95E-03 | 2.87E-03 |
| 30.01 | 1.39E-03 | 2.03E-03 | 3.00E-03 |
| 30.99 | 1.42E-03 | 2.11E-03 | 3.10E-03 |
| 31.58 | 1.44E-03 | 2.22E-03 | 3.16E-03 |
| 31.83 | 1.47E-03 | 2.34E-03 | 3.18E-03 |



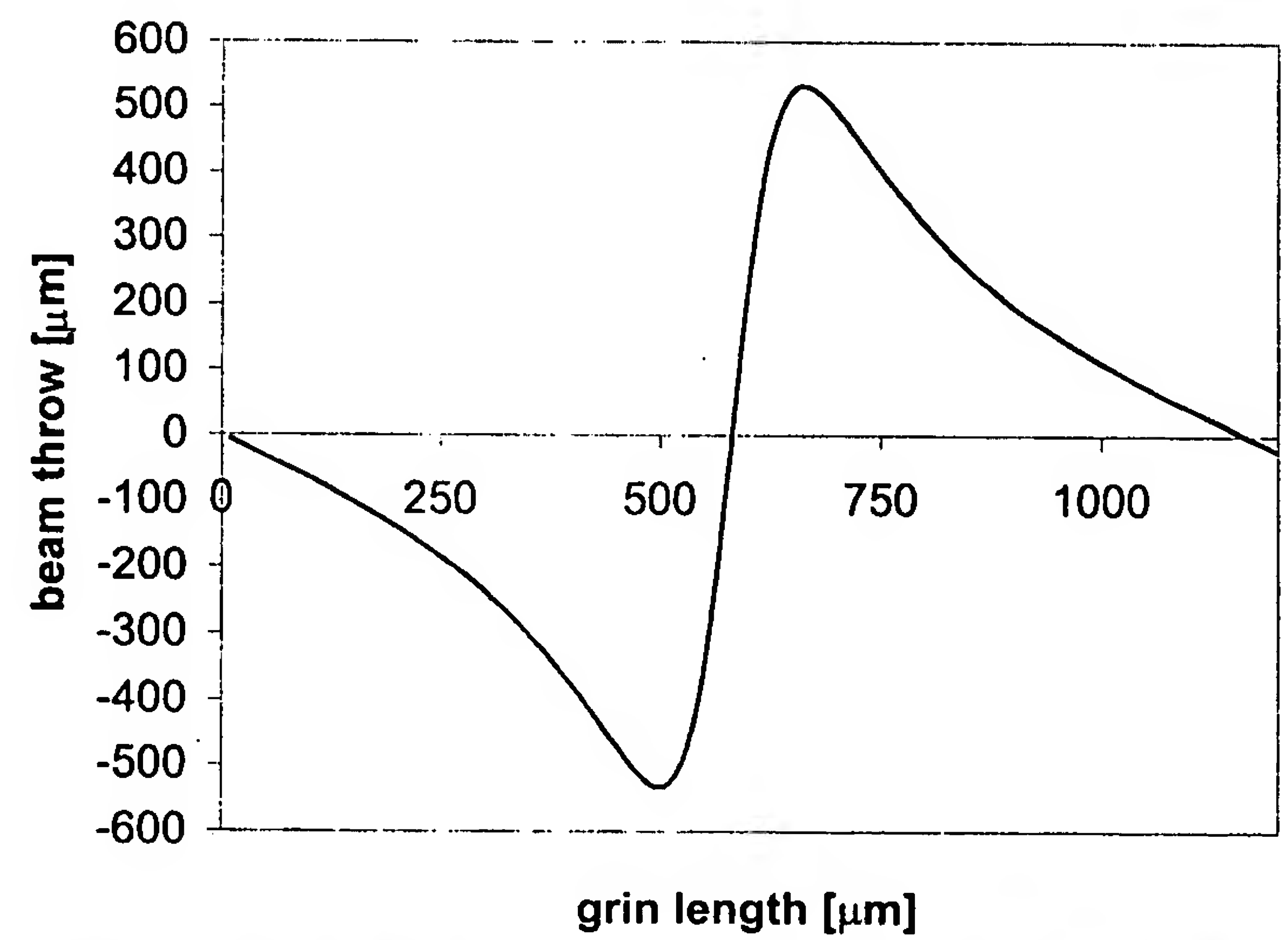



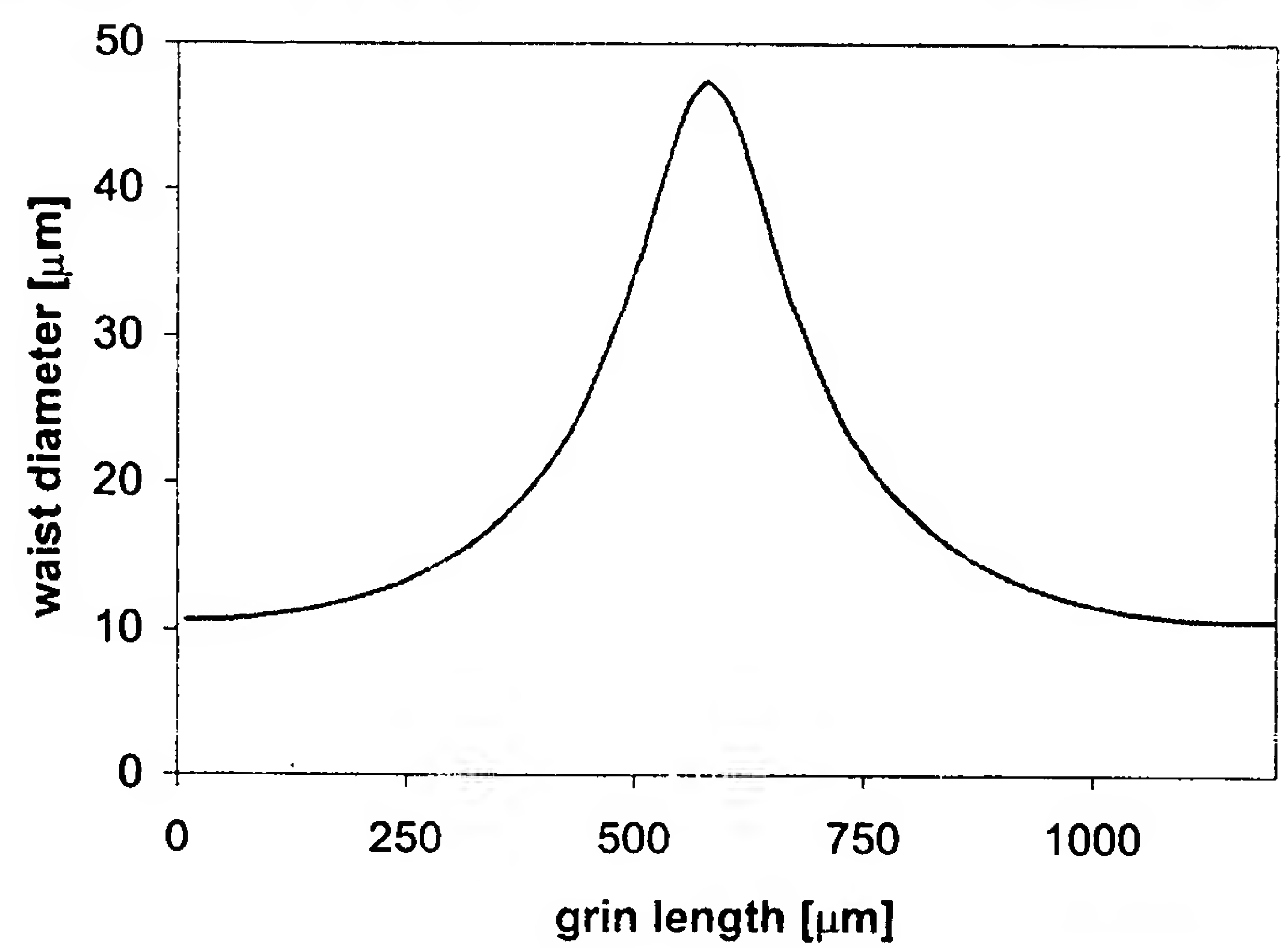
| | | | |
|---|---|---|---|
| 31.76 | 1.50E-03 | 2.47E-03 | 3.18E-03 |
| 31.36 | 1.53E-03 | 2.61E-03 | 3.14E-03 |
| 30.59 | 1.56E-03 | 2.75E-03 | 3.06E-03 |
| 29.44 | 1.59E-03 | 2.89E-03 | 2.94E-03 |
| 27.98 | 1.63E-03 | 3.06E-03 | 2.80E-03 |
| 26.82 | 1.67E-03 | 3.23E-03 | 2.68E-03 |
| 25.34 | 1.71E-03 | 3.42E-03 | 2.53E-03 |
| 24.10 | 1.75E-03 | 3.61E-03 | 2.41E-03 |
| 22.74 | 1.80E-03 | 3.78E-03 | 2.27E-03 |
| 21.77 | 1.85E-03 | 3.97E-03 | 2.18E-03 |
| 20.71 | 1.90E-03 | 4.11E-03 | 2.07E-03 |
| 19.65 | 1.95E-03 | 4.20E-03 | 1.97E-03 |
| 18.66 | 2.01E-03 | 4.24E-03 | 1.87E-03 |
| 17.75 | 2.08E-03 | 4.24E-03 | 1.77E-03 |
| 16.95 | 2.15E-03 | 4.18E-03 | 1.70E-03 |
| 16.32 | 2.22E-03 | 4.08E-03 | 1.63E-03 |
| 15.72 | 2.30E-03 | 3.92E-03 | 1.57E-03 |
| 15.17 | 2.39E-03 | 3.73E-03 | 1.52E-03 |
| 14.65 | 2.48E-03 | 3.56E-03 | 1.47E-03 |
| 14.18 | 2.58E-03 | 3.36E-03 | 1.42E-03 |
| 13.75 | 2.68E-03 | 3.18E-03 | 1.38E-03 |
| 13.36 | 2.80E-03 | 3.00E-03 | 1.34E-03 |
| 13.00 | 2.92E-03 | 2.85E-03 | 1.30E-03 |
| 12.68 | 3.06E-03 | 2.71E-03 | 1.27E-03 |
| 12.38 | 3.22E-03 | 2.57E-03 | 1.24E-03 |
| 12.11 | 3.40E-03 | 2.43E-03 | 1.21E-03 |
| 11.87 | 3.59E-03 | 2.30E-03 | 1.19E-03 |
| 11.66 | 3.80E-03 | 2.19E-03 | 1.17E-03 |
| 11.47 | 4.02E-03 | 2.09E-03 | 1.15E-03 |
| 11.30 | 4.23E-03 | 2.01E-03 | 1.13E-03 |
| 11.14 | 4.49E-03 | 1.93E-03 | 1.11E-03 |
| 11.01 | 4.75E-03 | 1.85E-03 | 1.10E-03 |
| 10.90 | 5.03E-03 | 1.79E-03 | 1.09E-03 |
| 10.80 | 5.33E-03 | 1.72E-03 | 1.08E-03 |
| 10.72 | 5.60E-03 | 1.67E-03 | 1.07E-03 |
| 10.66 | 5.90E-03 | 1.61E-03 | 1.07E-03 |
| 10.61 | 6.13E-03 | 1.56E-03 | 1.06E-03 |
| 10.58 | 6.28E-03 | 1.52E-03 | 1.06E-03 |
| 10.57 | 6.36E-03 | 1.48E-03 | 1.06E-03 |
| 10.57 | 6.39E-03 | 1.44E-03 | 1.06E-03 |
| 10.58 | 6.29E-03 | 1.40E-03 | 1.06E-03 |
| 10.61 | 6.15E-03 | 1.37E-03 | 1.06E-03 |
| 10.66 | 5.92E-03 | 1.34E-03 | 1.07E-03 |

| | | | |
|---|---|---|---|
| 10.72 | 5.62E-03 | 1.31E-03 | 1.07E-03 |
| 10.80 | 5.36E-03 | 1.28E-03 | 1.08E-03 |
| 10.89 | 5.06E-03 | 1.26E-03 | 1.09E-03 |
| 11.00 | 4.77E-03 | 1.23E-03 | 1.10E-03 |
| 11.13 | 4.52E-03 | 1.21E-03 | 1.11E-03 |
| 11.28 | 4.25E-03 | 1.20E-03 | 1.13E-03 |
| 11.45 | 4.04E-03 | 1.18E-03 | 1.15E-03 |
| 11.64 | 3.82E-03 | 1.16E-03 | 1.16E-03 |
| 11.86 | 3.61E-03 | 1.15E-03 | 1.19E-03 |
| 12.09 | 3.41E-03 | 1.13E-03 | 1.21E-03 |
| 12.36 | 3.23E-03 | 1.12E-03 | 1.24E-03 |
| 12.65 | 3.07E-03 | 1.11E-03 | 1.27E-03 |
| 12.97 | 2.93E-03 | 1.10E-03 | 1.30E-03 |
| 13.33 | 2.81E-03 | 1.09E-03 | 1.33E-03 |
| 13.72 | 2.69E-03 | 1.08E-03 | 1.37E-03 |
| 14.15 | 2.59E-03 | 1.08E-03 | 1.41E-03 |
| 14.61 | 2.49E-03 | 1.07E-03 | 1.46E-03 |
| 15.12 | 2.39E-03 | 1.07E-03 | 1.51E-03 |
| 15.68 | 2.31E-03 | 1.06E-03 | 1.57E-03 |
| 16.27 | 2.23E-03 | 1.06E-03 | 1.63E-03 |
| 16.90 | 2.15E-03 | 1.06E-03 | 1.69E-03 |
| 17.68 | 2.08E-03 | 1.06E-03 | 1.77E-03 |
| 18.58 | 2.02E-03 | 1.06E-03 | 1.86E-03 |
| 19.57 | 1.96E-03 | 1.06E-03 | 1.96E-03 |
| 20.62 | 1.90E-03 | 1.06E-03 | 2.06E-03 |
| 21.69 | 1.85E-03 | 1.06E-03 | 2.17E-03 |
| 22.62 | 1.80E-03 | 1.06E-03 | 2.26E-03 |
| 23.99 | 1.75E-03 | 1.07E-03 | 2.40E-03 |
| 25.22 | 1.71E-03 | 1.07E-03 | 2.52E-03 |
| 26.71 | 1.67E-03 | 1.08E-03 | 2.67E-03 |
| 27.90 | 1.63E-03 | 1.09E-03 | 2.79E-03 |
| 29.33 | 1.60E-03 | 1.10E-03 | 2.93E-03 |
| 30.51 | 1.56E-03 | 1.11E-03 | 3.05E-03 |
| 31.31 | 1.53E-03 | 1.12E-03 | 3.13E-03 |
| 31.74 | 1.50E-03 | 1.13E-03 | 3.17E-03 |
| 31.94 | 1.47E-03 | 1.14E-03 | 3.19E-03 |
| 31.62 | 1.44E-03 | 1.15E-03 | 3.16E-03 |
| 31.05 | 1.42E-03 | 1.17E-03 | 3.11E-03 |
| 30.10 | 1.39E-03 | 1.19E-03 | 3.01E-03 |
| 28.80 | 1.37E-03 | 1.21E-03 | 2.88E-03 |
| 27.50 | 1.35E-03 | 1.23E-03 | 2.75E-03 |
| 26.17 | 1.33E-03 | 1.25E-03 | 2.62E-03 |
| 24.75 | 1.31E-03 | 1.27E-03 | 2.47E-03 |

Beam throw (=fiber-to-fiber working distance/2), beam waist (2*w0), and beam width (2*r) at exit of grin lens as a function of grin length:
Beam waist and beam width taken at 1/e2 intensity level, wavelength=1550nm, SMF28 - grin fiber assembly
g = 2.7 mm-1, n0=1.4815, NA=0.16, core diam=80 micrometer

| grin length [μm] | WD/2 [μm] | 2*w0 [μm] | 2*r [μm] |
|---|---|---|---|
| 10 | -6.41 | 10.57 | 10.63 |
| 20 | -12.84 | 10.58 | 10.82 |
| 30 | -19.27 | 10.60 | 11.17 |
| 40 | -25.74 | 10.62 | 11.68 |
| 50 | -32.23 | 10.66 | 12.23 |
| 60 | -38.77 | 10.70 | 12.87 |
| 70 | -45.35 | 10.75 | 13.64 |
| 80 | -51.99 | 10.81 | 14.38 |
| 90 | -58.70 | 10.87 | 15.29 |
| 100 | -65.48 | 10.94 | 16.18 |
| 110 | -72.35 | 11.03 | 17.05 |
| 120 | -79.32 | 11.12 | 18.06 |
| 130 | -86.39 | 11.22 | 19.05 |
| 140 | -93.58 | 11.33 | 20.03 |
| 150 | -100.90 | 11.45 | 21.00 |
| 160 | -108.35 | 11.58 | 21.96 |
| 170 | -115.97 | 11.72 | 22.91 |
| 180 | -123.74 | 11.88 | 23.85 |
| 190 | -131.71 | 12.04 | 24.83 |
| 200 | -139.86 | 12.22 | 25.83 |
| 210 | -148.23 | 12.41 | 26.81 |
| 220 | -156.84 | 12.62 | 27.79 |
| 230 | -165.69 | 12.84 | 28.74 |
| 240 | -174.81 | 13.08 | 29.68 |
| 250 | -184.22 | 13.34 | 30.60 |
| 260 | -193.94 | 13.62 | 31.51 |
| 270 | -204.00 | 13.92 | 32.39 |
| 280 | -214.42 | 14.24 | 33.25 |
| 290 | -225.24 | 14.58 | 34.08 |
| 300 | -236.47 | 14.95 | 34.89 |
| 310 | -248.15 | 15.35 | 35.68 |
| 320 | -260.30 | 15.78 | 36.43 |
| 330 | -272.97 | 16.24 | 37.15 |
| 340 | -286.18 | 16.74 | 37.90 |
| 350 | -299.97 | 17.28 | 38.68 |
| 360 | -314.36 | 17.86 | 39.42 |
| 370 | -329.37 | 18.49 | 40.14 |



| | | | |
|---|---|---|---|
| 380 | -345.04 | 19.17 | 40.81 |
| 390 | -361.35 | 19.90 | 41.44 |
| 400 | -378.30 | 20.69 | 42.00 |
| 410 | -395.84 | 21.54 | 42.50 |
| 420 | -413.91 | 22.45 | 42.90 |
| 430 | -432.36 | 23.45 | 43.41 |
| 440 | -450.97 | 24.68 | 43.99 |
| 450 | -469.41 | 26.03 | 44.36 |
| 460 | -487.17 | 27.49 | 44.71 |
| 470 | -503.52 | 29.06 | 45.12 |
| 480 | -517.40 | 30.67 | 45.47 |
| 490 | -527.37 | 32.17 | 45.75 |
| 500 | -531.44 | 34.34 | 46.32 |
| 510 | -527.00 | 36.04 | 46.30 |
| 520 | -510.83 | 38.29 | 46.53 |
| 530 | -479.26 | 40.33 | 46.78 |
| 540 | -428.65 | 42.38 | 47.01 |
| 550 | -356.31 | 44.40 | 46.93 |
| 560 | -261.82 | 45.88 | 47.33 |
| 570 | -148.29 | 46.77 | 47.27 |
| 580 | -22.80 | 47.40 | 47.41 |
| 590 | 104.60 | 46.95 | 47.20 |
| 600 | 223.38 | 46.27 | 47.35 |
| 610 | 325.20 | 45.00 | 47.14 |
| 620 | 405.52 | 43.15 | 47.04 |
| 630 | 463.63 | 40.92 | 46.62 |
| 640 | 501.57 | 39.07 | 46.51 |
| 650 | 522.78 | 36.79 | 46.27 |
| 660 | 530.99 | 34.86 | 46.07 |
| 670 | 529.61 | 32.83 | 45.84 |
| 680 | 521.49 | 31.23 | 45.54 |
| 690 | 508.80 | 29.63 | 45.14 |
| 700 | 493.18 | 28.04 | 44.91 |
| 710 | 475.83 | 26.53 | 44.44 |
| 720 | 457.56 | 25.14 | 44.15 |
| 730 | 438.97 | 23.88 | 43.63 |
| 740 | 420.43 | 22.78 | 43.02 |
| 750 | 402.21 | 21.86 | 42.65 |
| 760 | 384.46 | 20.99 | 42.19 |
| 770 | 367.30 | 20.18 | 41.64 |
| 780 | 350.76 | 19.42 | 41.04 |
| 790 | 334.86 | 18.73 | 40.38 |

Working point for 1x2 design: grin length 830+-20 micrometer
working distance 550+-50 micrometer
waist diameter 16.4 +- 1 micrometer

Working point for 2x2 design: grin length 990+-20 micrometer
working distance 238+-50 micrometer
waist diameter 11.8 +- 1 micrometer

Largest beam width in Grin fiber: 47.3 micrometer = 59% of core diameters
(would like to stay <60%)

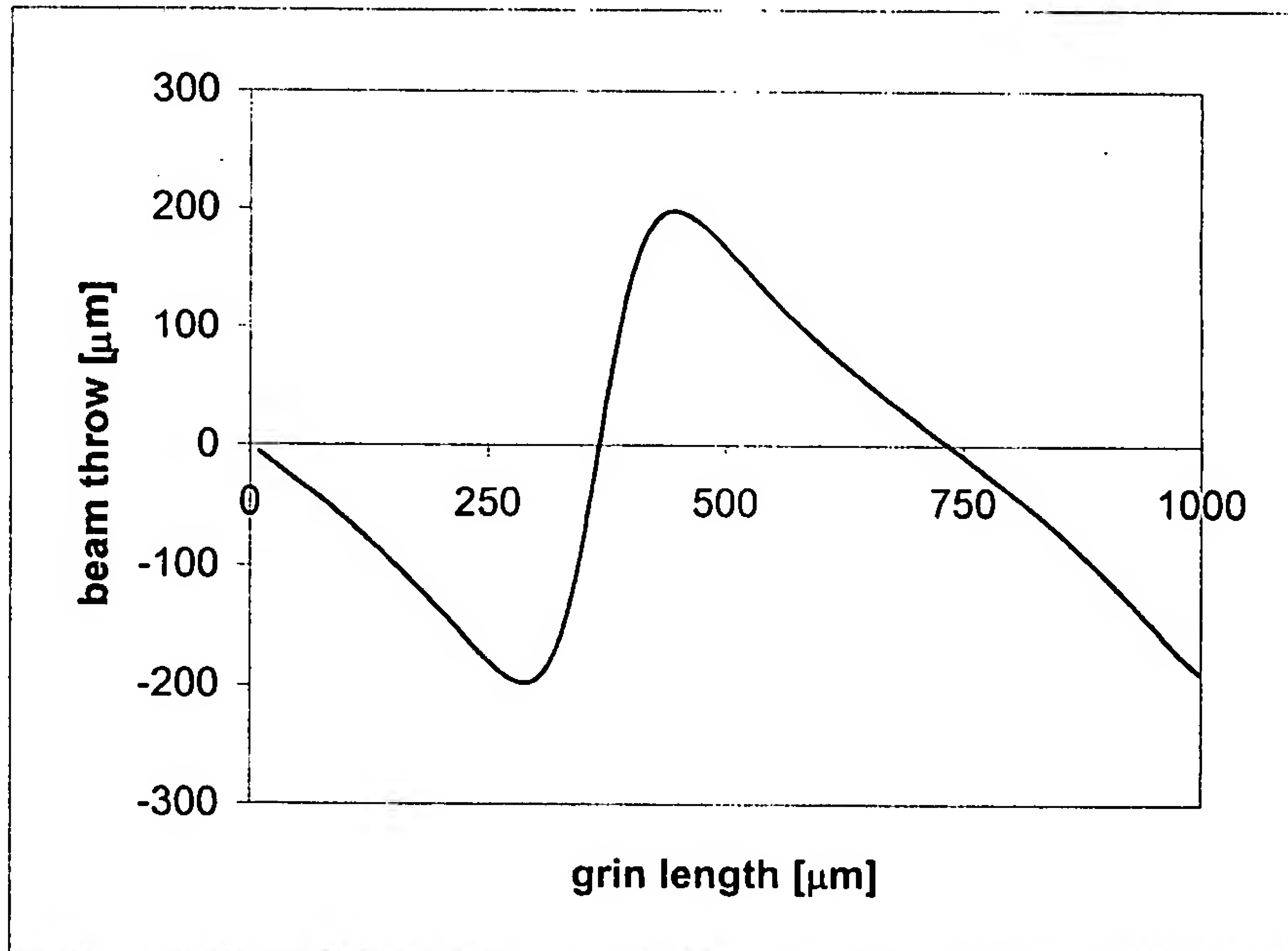
| | | | |
|---|---|---|---|
| 800 | 319.62 | 18.08 | 39.68 |
| 810 | 305.01 | 17.48 | 38.94 |
| 820 | 291.01 | 16.93 | 38.18 |
| 830 | 277.60 | 16.42 | 37.40 |
| 840 | 264.74 | 15.94 | 36.69 |
| 850 | 252.41 | 15.50 | 35.95 |
| 860 | 240.56 | 15.09 | 35.18 |
| 870 | 229.18 | 14.71 | 34.37 |
| 880 | 218.22 | 14.36 | 33.55 |
| 890 | 207.66 | 14.03 | 32.70 |
| 900 | 197.48 | 13.72 | 31.82 |
| 910 | 187.64 | 13.44 | 30.93 |
| 920 | 178.12 | 13.17 | 30.01 |
| 930 | 168.90 | 12.93 | 29.08 |
| 940 | 159.95 | 12.70 | 28.13 |
| 950 | 151.26 | 12.49 | 27.16 |
| 960 | 142.81 | 12.29 | 26.18 |
| 970 | 134.58 | 12.10 | 25.18 |
| 980 | 126.55 | 11.93 | 24.18 |
| 990 | 118.71 | 11.77 | 23.25 |
| 1000 | 111.04 | 11.63 | 22.30 |
| 1010 | 103.53 | 11.49 | 21.34 |
| 1020 | 96.16 | 11.37 | 20.38 |
| 1030 | 88.93 | 11.26 | 19.40 |
| 1040 | 81.82 | 11.15 | 18.41 |
| 1050 | 74.82 | 11.06 | 17.41 |
| 1060 | 67.91 | 10.97 | 16.48 |
| 1070 | 61.10 | 10.90 | 15.61 |
| 1080 | 54.37 | 10.83 | 14.71 |
| 1090 | 47.70 | 10.77 | 13.91 |
| 1100 | 41.10 | 10.72 | 13.15 |
| 1110 | 34.55 | 10.67 | 12.44 |
| 1120 | 28.04 | 10.64 | 11.87 |
| 1130 | 21.57 | 10.61 | 11.34 |
| 1140 | 15.12 | 10.59 | 10.91 |
| 1150 | 8.69 | 10.57 | 10.68 |
| 1160 | 2.28 | 10.57 | 10.57 |
| 1170 | -4.13 | 10.57 | 10.59 |
| 1180 | -10.55 | 10.58 | 10.74 |
| 1190 | -16.98 | 10.59 | 11.00 |
| 1200 | -23.44 | 10.61 | 11.49 |

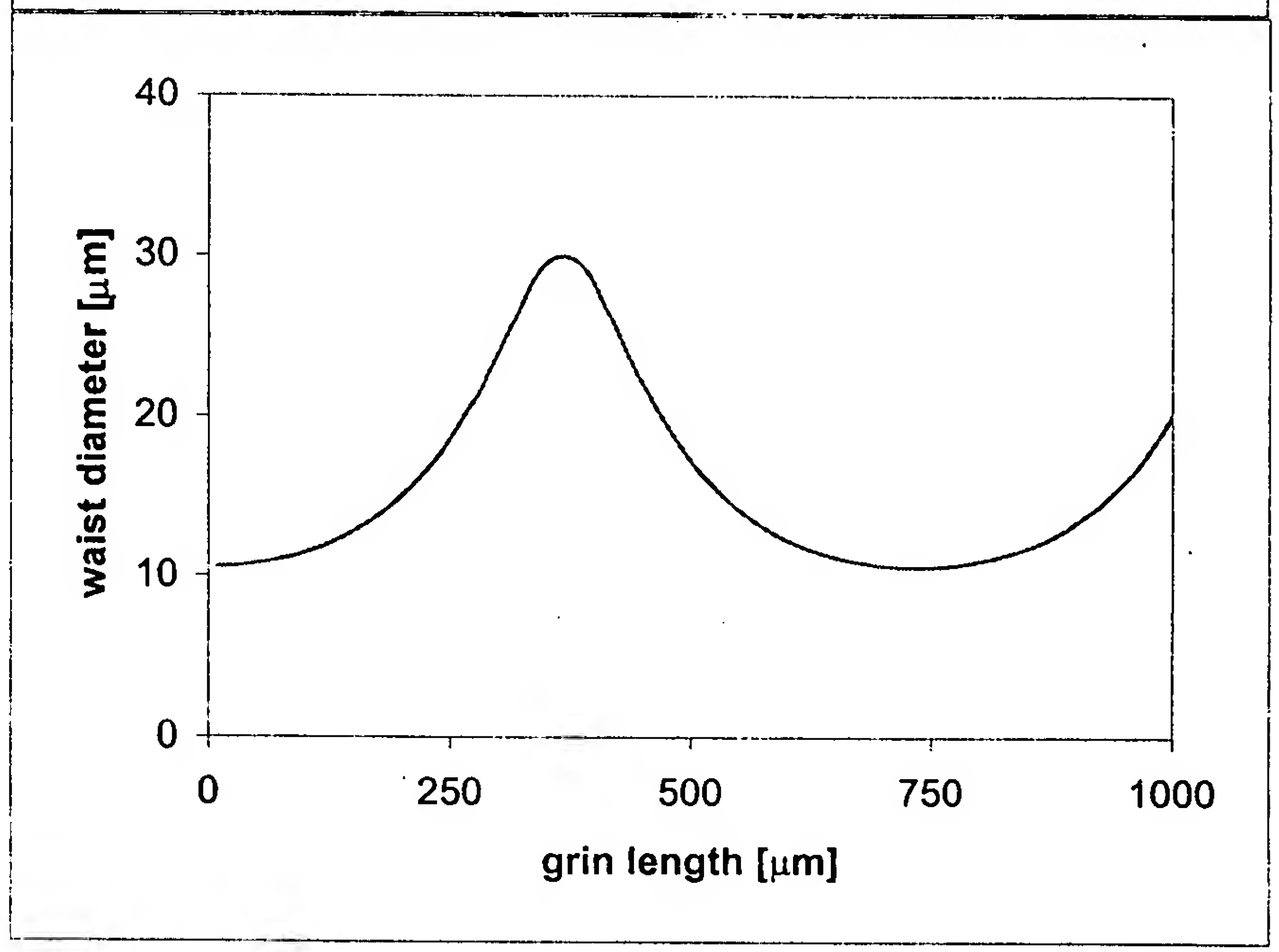
For a fixed working distance of 550 +- 50 micrometer and varying the g-parameter, we get the following grin lengths and waist diameters:

| g [mm-1] | grin lengths [μm] | 2*w0 [μm] |
|---|---|---|
| 2.5 | 920 | 15.35 |
| 2.52 | 911 | 15.41 |
| 2.54 | 902 | 14.48 |
| 2.56 | 892 | 15.6 |
| 2.58 | 884 | 15.64 |
| 2.6 | 875 | 15.72 |
| 2.62 | 866 | 15.82 |
| 2.64 | 858 | 15.88 |
| 2.66 | 849 | 16 |
| 2.68 | 841 | 16.06 |
| 2.7 | 833 | 16.13 |
| 2.72 | 825 | 16.22 |
| 2.74 | 817 | 16.3 |
| 2.76 | 809 | 16.4 |
| 2.78 | 801 | 16.5 |
| 2.8 | 794 | 16.56 |
| 2.82 | 786 | 16.68 |
| 2.84 | 779 | 16.75 |
| 2.86 | 772 | 16.82 |
| 2.88 | 764 | 16.96 |
| 2.9 | 757 | 17.05 |

Beam throw (=fiber-to-fiber working distance/2), beam waist (2*w0), and beam width (2*r) at exit of grin lens as a function of grin length:
Beam waist and beam width taken at 1/e2 intensity level, wavelength=1550nm, SMF28 - grin fiber assembly
g = 4.2778 mm-1, n0=1.471, NA=0.267, core diam=85 micrometer (used in **Gradissimo** fibers)

| grin length [μm] | WD/2 [μm] | 2*w0 [μm] | 2*r [μm] |
|---|---|---|---|
| 10 | -5.96 | 10.57 | 10.63 |
| 20 | -11.93 | 10.60 | 10.80 |
| 30 | -17.94 | 10.64 | 11.11 |
| 40 | -23.98 | 10.70 | 11.60 |
| 50 | -30.08 | 10.78 | 12.14 |
| 60 | -36.25 | 10.88 | 12.71 |
| 70 | -42.50 | 11.00 | 13.40 |
| 80 | -48.85 | 11.14 | 14.16 |
| 90 | -55.32 | 11.30 | 14.89 |
| 100 | -61.91 | 11.48 | 15.68 |
| 110 | -68.65 | 11.69 | 16.53 |
| 120 | -75.55 | 11.92 | 17.38 |
| 130 | -82.62 | 12.18 | 18.20 |
| 140 | -89.88 | 12.47 | 19.02 |
| 150 | -97.34 | 12.79 | 19.83 |
| 160 | -105.01 | 13.14 | 20.63 |
| 170 | -112.90 | 13.54 | 21.42 |
| 180 | -120.99 | 13.97 | 22.21 |
| 190 | -129.29 | 14.44 | 22.97 |
| 200 | -137.77 | 14.95 | 23.70 |
| 210 | -146.38 | 15.51 | 24.38 |
| 220 | -155.06 | 16.10 | 24.99 |
| 230 | -163.68 | 16.80 | 25.58 |
| 240 | -172.10 | 17.64 | 26.24 |
| 250 | -180.05 | 18.57 | 26.69 |
| 260 | -187.20 | 19.56 | 27.32 |
| 270 | -193.06 | 20.57 | 27.76 |
| 280 | -196.96 | 21.44 | 28.31 |
| 290 | -198.03 | 22.72 | 28.54 |
| 300 | -195.16 | 23.87 | 28.91 |
| 310 | -187.04 | 25.27 | 29.22 |
| 320 | -172.28 | 26.36 | 29.44 |
| 330 | -149.67 | 27.71 | 29.66 |
| 340 | -118.61 | 28.79 | 29.91 |
| 350 | -79.56 | 29.51 | 30.05 |
| 360 | -34.45 | 29.88 | 29.98 |
| 370 | 13.50 | 29.94 | 29.96 |
| 380 | 60.32 | 29.71 | 30.03 |



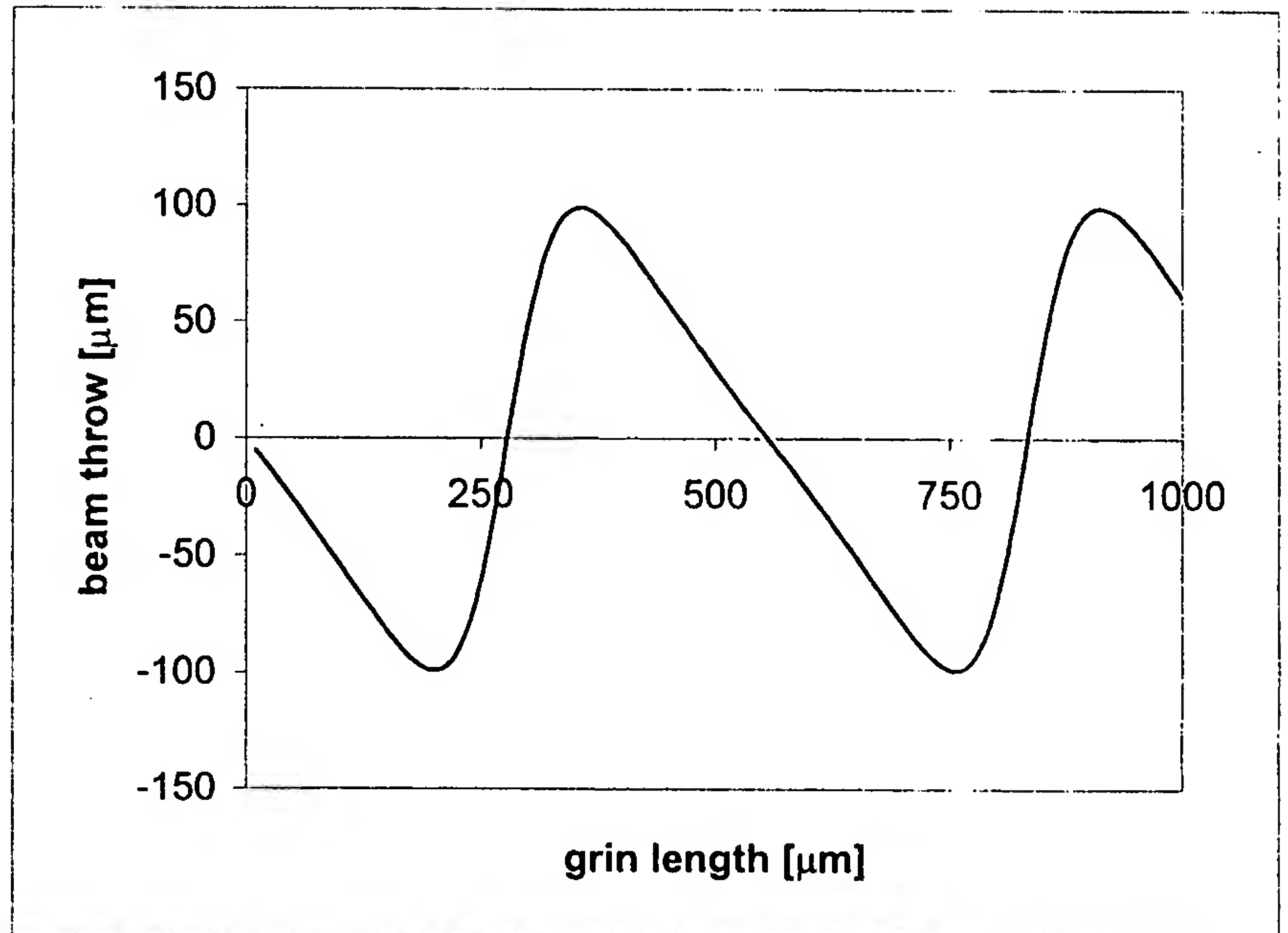



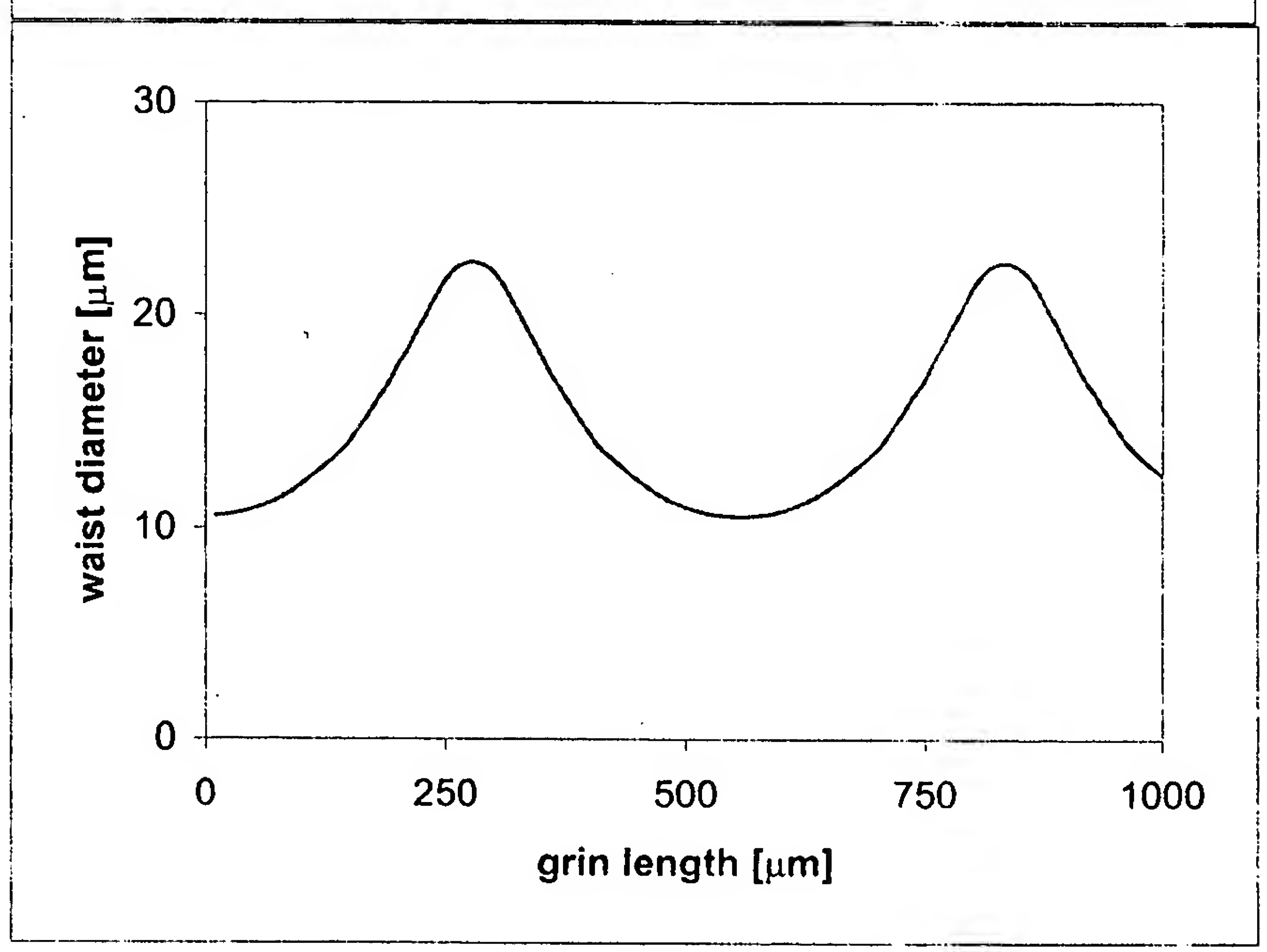
| | | | |
|---|---|---|---|
| 390 | 102.36 | 29.15 | 30.01 |
| 400 | 137.07 | 28.23 | 29.68 |
| 410 | 163.37 | 26.97 | 29.63 |
| 420 | 181.45 | 25.80 | 29.33 |
| 430 | 192.33 | 24.51 | 29.00 |
| 440 | 197.33 | 23.24 | 28.67 |
| 450 | 197.84 | 22.07 | 28.48 |
| 460 | 195.06 | 20.98 | 27.92 |
| 470 | 189.97 | 20.01 | 27.58 |
| 480 | 183.32 | 19.00 | 26.97 |
| 490 | 175.67 | 18.04 | 26.46 |
| 500 | 167.42 | 17.16 | 25.89 |
| 510 | 158.86 | 16.36 | 25.23 |
| 520 | 150.19 | 15.76 | 24.66 |
| 530 | 141.54 | 15.19 | 24.01 |
| 540 | 133.00 | 14.66 | 23.30 |
| 550 | 124.62 | 14.17 | 22.54 |
| 560 | 116.43 | 13.72 | 21.77 |
| 570 | 108.45 | 13.31 | 20.98 |
| 580 | 100.69 | 12.94 | 20.18 |
| 590 | 93.14 | 12.60 | 19.37 |
| 600 | 85.79 | 12.30 | 18.56 |
| 610 | 78.64 | 12.03 | 17.74 |
| 620 | 71.66 | 11.79 | 16.90 |
| 630 | 64.85 | 11.57 | 16.06 |
| 640 | 58.20 | 11.37 | 15.21 |
| 650 | 51.68 | 11.21 | 14.48 |
| 660 | 45.28 | 11.06 | 13.73 |
| 670 | 38.98 | 10.93 | 12.97 |
| 680 | 32.78 | 10.82 | 12.39 |
| 690 | 26.65 | 10.74 | 11.83 |
| 700 | 20.59 | 10.67 | 11.32 |
| 710 | 14.57 | 10.62 | 10.91 |
| 720 | 8.58 | 10.58 | 10.69 |
| 730 | 2.62 | 10.57 | 10.58 |
| 740 | -3.34 | 10.57 | 10.58 |
| 750 | -9.31 | 10.59 | 10.71 |
| 760 | -15.29 | 10.62 | 10.95 |
| 770 | -21.32 | 10.68 | 11.37 |
| 780 | -27.39 | 10.75 | 11.90 |
| 790 | -33.53 | 10.84 | 12.46 |
| 800 | -39.74 | 10.95 | 13.06 |
| 810 | -46.05 | 11.07 | 13.83 |

| | | | |
|---|---|---|---|
| 820 | -52.46 | 11.22 | 14.57 |
| 830 | -59.00 | 11.40 | 15.30 |
| 840 | -65.67 | 11.59 | 16.16 |
| 850 | -72.50 | 11.81 | 17.01 |
| 860 | -79.49 | 12.06 | 17.84 |
| 870 | -86.67 | 12.34 | 18.66 |
| 880 | -94.04 | 12.64 | 19.47 |
| 890 | -101.62 | 12.98 | 20.28 |
| 900 | -109.41 | 13.36 | 21.07 |
| 910 | -117.41 | 13.77 | 21.86 |
| 920 | -125.62 | 14.23 | 22.64 |
| 930 | -134.03 | 14.72 | 23.38 |
| 940 | -142.59 | 15.26 | 24.09 |
| 950 | -151.24 | 15.83 | 24.73 |
| 960 | -159.91 | 16.45 | 25.29 |
| 970 | -168.44 | 17.26 | 25.97 |
| 980 | -176.63 | 18.15 | 26.52 |
| 990 | -184.19 | 19.12 | 27.05 |
| 1000 | -190.68 | 20.13 | 27.64 |

Beam throw (=fiber-to-fiber working distance/2), beam waist (2*w0), and beam width (2*r) at exit of grin lens as a function of grin length:
Beam waist and beam width taken at 1/e2 intensity level, wavelength=1550nm, SMF28 - grin fiber assembly
g = 5.65 mm-1, n0=1.486, NA=0.2, core diam=50 micrometer (**Corning InfiniCor CL2000**)

| grin length [μm] | WD/2 [μm] | 2*w0 [μm] | 2*r [μm] |
|---|---|---|---|
| 10 | -5.25 | 10.58 | 10.62 |
| 20 | -10.51 | 10.62 | 10.78 |
| 30 | -15.80 | 10.69 | 11.03 |
| 40 | -21.12 | 10.79 | 11.43 |
| 50 | -26.48 | 10.91 | 11.93 |
| 60 | -31.89 | 11.07 | 12.47 |
| 70 | -37.35 | 11.26 | 13.04 |
| 80 | -42.88 | 11.48 | 13.64 |
| 90 | -48.47 | 11.73 | 14.26 |
| 100 | -54.11 | 12.02 | 14.93 |
| 110 | -59.79 | 12.35 | 15.62 |
| 120 | -65.48 | 12.72 | 16.29 |
| 130 | -71.13 | 13.11 | 16.92 |
| 140 | -76.70 | 13.53 | 17.58 |
| 150 | -82.06 | 14.04 | 18.26 |
| 160 | -87.11 | 14.69 | 18.88 |
| 170 | -91.63 | 15.39 | 19.36 |
| 180 | -95.37 | 16.11 | 19.96 |
| 190 | -97.99 | 16.74 | 20.44 |
| 200 | -99.04 | 17.63 | 20.94 |
| 210 | -97.96 | 18.29 | 21.20 |
| 220 | -94.13 | 19.27 | 21.57 |
| 230 | -86.90 | 20.02 | 21.87 |
| 240 | -75.74 | 20.92 | 22.04 |
| 250 | -60.41 | 21.65 | 22.34 |
| 260 | -41.18 | 22.14 | 22.48 |
| 270 | -18.97 | 22.39 | 22.47 |
| 280 | 4.73 | 22.45 | 22.45 |
| 290 | 28.05 | 22.32 | 22.48 |
| 300 | 49.23 | 21.98 | 22.45 |
| 310 | 66.99 | 21.39 | 22.21 |
| 320 | 80.66 | 20.56 | 22.03 |
| 330 | 90.21 | 19.76 | 21.67 |
| 340 | 96.02 | 18.90 | 21.41 |
| 350 | 98.68 | 18.03 | 21.05 |
| 360 | 98.84 | 17.21 | 20.65 |
| 370 | 97.11 | 16.51 | 20.30 |



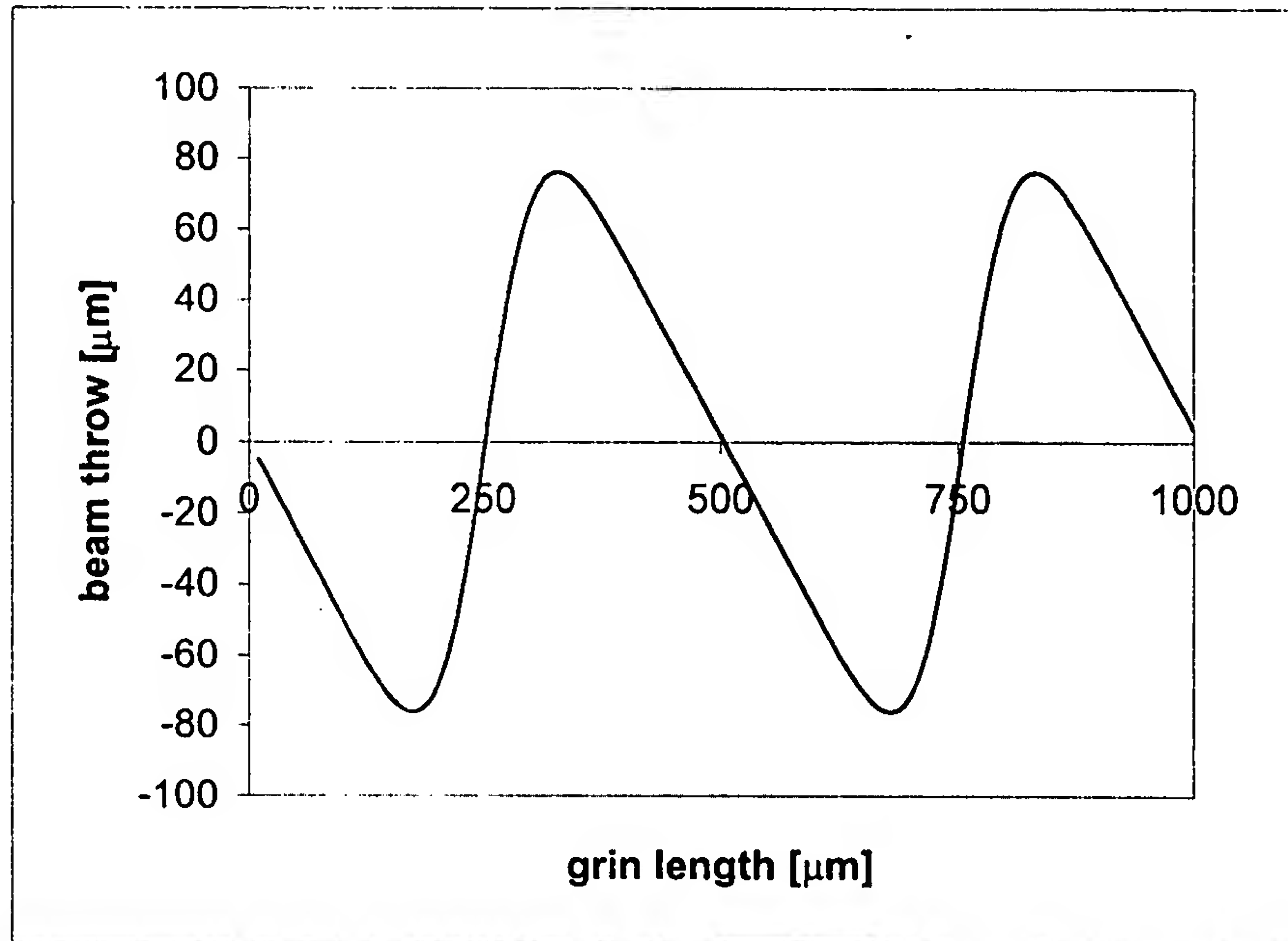



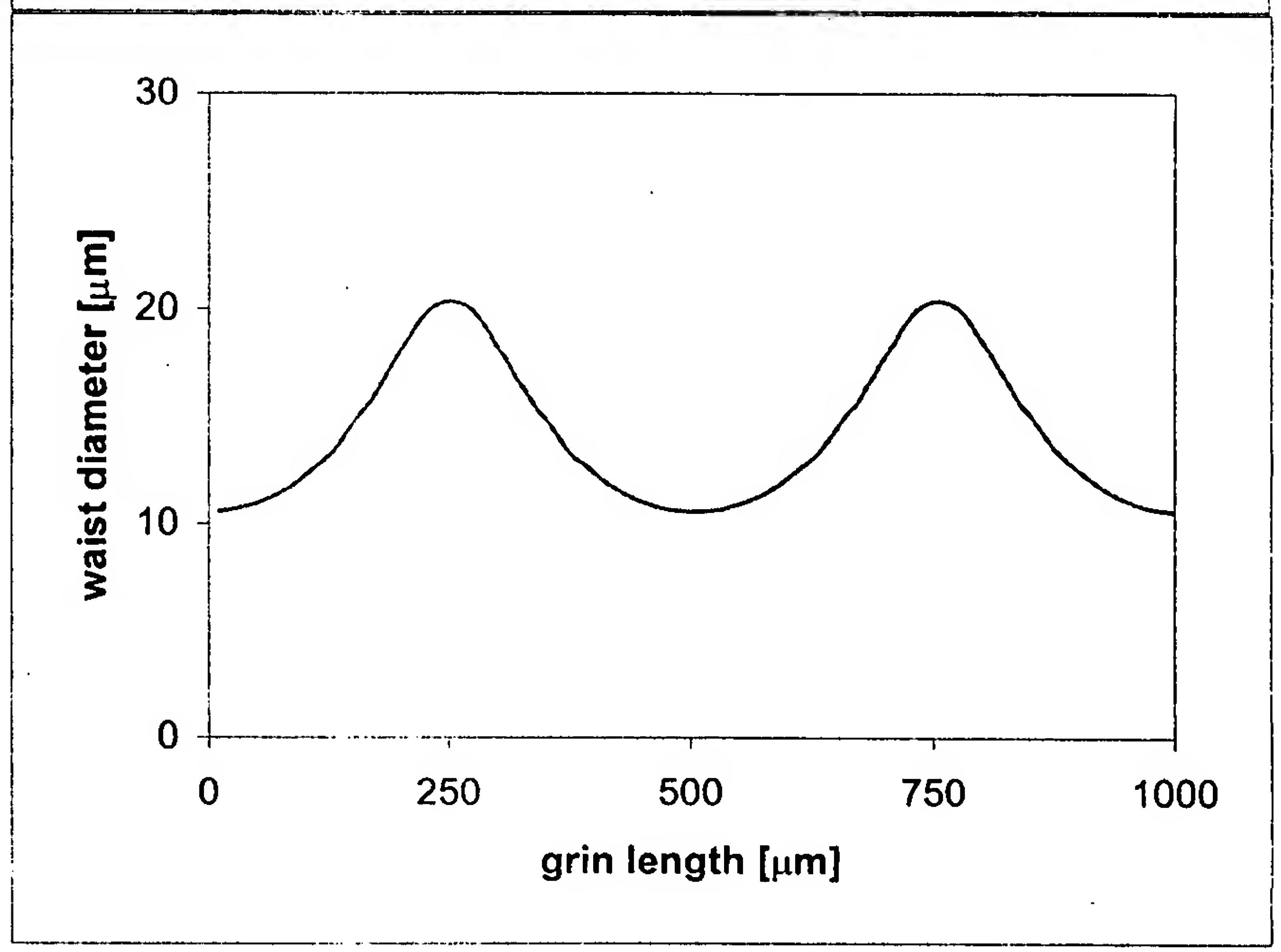
| | | | |
|---|---|---|---|
| 380 | 94.00 | 15.82 | 19.70 |
| 390 | 89.91 | 15.10 | 19.19 |
| 400 | 85.16 | 14.42 | 18.64 |
| 410 | 79.97 | 13.80 | 17.99 |
| 420 | 74.51 | 13.37 | 17.31 |
| 430 | 68.90 | 12.95 | 16.67 |
| 440 | 63.22 | 12.57 | 16.02 |
| 450 | 57.53 | 12.22 | 15.35 |
| 460 | 51.87 | 11.90 | 14.65 |
| 470 | 46.25 | 11.63 | 14.01 |
| 480 | 40.68 | 11.39 | 13.40 |
| 490 | 35.18 | 11.18 | 12.81 |
| 500 | 29.73 | 11.00 | 12.25 |
| 510 | 24.34 | 10.86 | 11.73 |
| 520 | 19.00 | 10.74 | 11.25 |
| 530 | 13.70 | 10.66 | 10.92 |
| 540 | 8.42 | 10.60 | 10.70 |
| 550 | 3.17 | 10.57 | 10.59 |
| 560 | -2.08 | 10.57 | 10.57 |
| 570 | -7.34 | 10.59 | 10.67 |
| 580 | -12.61 | 10.64 | 10.87 |
| 590 | -17.90 | 10.72 | 11.16 |
| 600 | -23.24 | 10.83 | 11.62 |
| 610 | -28.62 | 10.97 | 12.14 |
| 620 | -34.05 | 11.14 | 12.69 |
| 630 | -39.54 | 11.34 | 13.28 |
| 640 | -45.09 | 11.57 | 13.88 |
| 650 | -50.70 | 11.84 | 14.51 |
| 660 | -56.36 | 12.15 | 15.21 |
| 670 | -62.05 | 12.49 | 15.89 |
| 680 | -67.73 | 12.87 | 16.54 |
| 690 | -73.36 | 13.28 | 17.17 |
| 700 | -78.85 | 13.70 | 17.85 |
| 710 | -84.11 | 14.29 | 18.51 |
| 720 | -88.97 | 14.96 | 19.09 |
| 730 | -93.22 | 15.67 | 19.55 |
| 740 | -96.57 | 16.38 | 20.20 |
| 750 | -98.62 | 16.99 | 20.48 |
| 760 | -98.90 | 17.87 | 20.94 |
| 770 | -96.81 | 18.70 | 21.30 |
| 780 | -91.70 | 19.60 | 21.63 |
| 790 | -82.97 | 20.36 | 22.00 |

| | | | |
|---|---|---|---|
| 800 | -70.16 | 21.24 | 22.13 |
| 810 | -53.22 | 21.88 | 22.42 |
| 820 | -32.66 | 22.27 | 22.49 |
| 830 | -9.64 | 22.43 | 22.45 |
| 840 | 14.13 | 22.42 | 22.46 |
| 850 | 36.79 | 22.21 | 22.49 |
| 860 | 56.74 | 21.78 | 22.39 |
| 870 | 72.92 | 21.09 | 22.05 |
| 880 | 84.93 | 20.17 | 21.94 |
| 890 | 92.93 | 19.45 | 21.62 |
| 900 | 97.41 | 18.50 | 21.22 |
| 910 | 99.01 | 17.71 | 20.82 |
| 920 | 98.35 | 16.84 | 20.48 |
| 930 | 96.02 | 16.25 | 20.09 |
| 940 | 92.48 | 15.54 | 19.42 |
| 950 | 88.09 | 14.83 | 18.99 |
| 960 | 83.14 | 14.17 | 18.39 |
| 970 | 77.83 | 13.62 | 17.72 |
| 980 | 72.30 | 13.20 | 17.04 |
| 990 | 66.65 | 12.80 | 16.42 |
| 1000 | 60.97 | 12.42 | 15.76 |

Beam throw (=fiber-to-fiber working distance/2), beam waist (2*w0), and beam width (2*r) at exit of grin lens as a function of grin length:
Beam waist and beam width taken at 1/e2 intensity level, wavelength=1550nm, SMF28 - grin fiber assembly
g = 6.237 mm-1, n0=1.487, NA=0.275, core diam=62.5 micrometer (**Corning InfiniCor CL1000**)

| grin length [μm] | WD/2 [μm] | 2*w0 [μm] | 2*r [μm] |
|---|---|---|---|
| 10 | -4.92 | 10.58 | 10.62 |
| 20 | -9.85 | 10.63 | 10.77 |
| 30 | -14.79 | 10.71 | 11.01 |
| 40 | -19.75 | 10.82 | 11.35 |
| 50 | -24.74 | 10.96 | 11.82 |
| 60 | -29.75 | 11.14 | 12.34 |
| 70 | -34.77 | 11.36 | 12.89 |
| 80 | -39.81 | 11.61 | 13.47 |
| 90 | -44.84 | 11.90 | 14.07 |
| 100 | -49.83 | 12.22 | 14.68 |
| 110 | -54.73 | 12.57 | 15.29 |
| 120 | -59.48 | 12.94 | 15.90 |
| 130 | -63.98 | 13.43 | 16.46 |
| 140 | -68.09 | 14.02 | 16.95 |
| 150 | -71.62 | 14.66 | 17.59 |
| 160 | -74.33 | 15.27 | 18.09 |
| 170 | -75.89 | 15.82 | 18.55 |
| 180 | -75.91 | 16.56 | 18.90 |
| 190 | -73.92 | 17.30 | 19.28 |
| 200 | -69.43 | 18.04 | 19.56 |
| 210 | -62.01 | 18.72 | 19.87 |
| 220 | -51.40 | 19.44 | 20.09 |
| 230 | -37.66 | 19.93 | 20.31 |
| 240 | -21.32 | 20.22 | 20.34 |
| 250 | -3.39 | 20.32 | 20.32 |
| 260 | 14.80 | 20.27 | 20.34 |
| 270 | 31.87 | 20.06 | 20.34 |
| 280 | 46.66 | 19.65 | 20.20 |
| 290 | 58.46 | 19.01 | 19.87 |
| 300 | 67.04 | 18.25 | 19.72 |
| 310 | 72.57 | 17.60 | 19.40 |
| 320 | 75.43 | 16.77 | 19.00 |
| 330 | 76.10 | 16.17 | 18.78 |
| 340 | 75.06 | 15.46 | 18.18 |
| 350 | 72.74 | 14.89 | 17.81 |
| 360 | 69.48 | 14.25 | 17.20 |
| 370 | 65.56 | 13.64 | 16.65 |



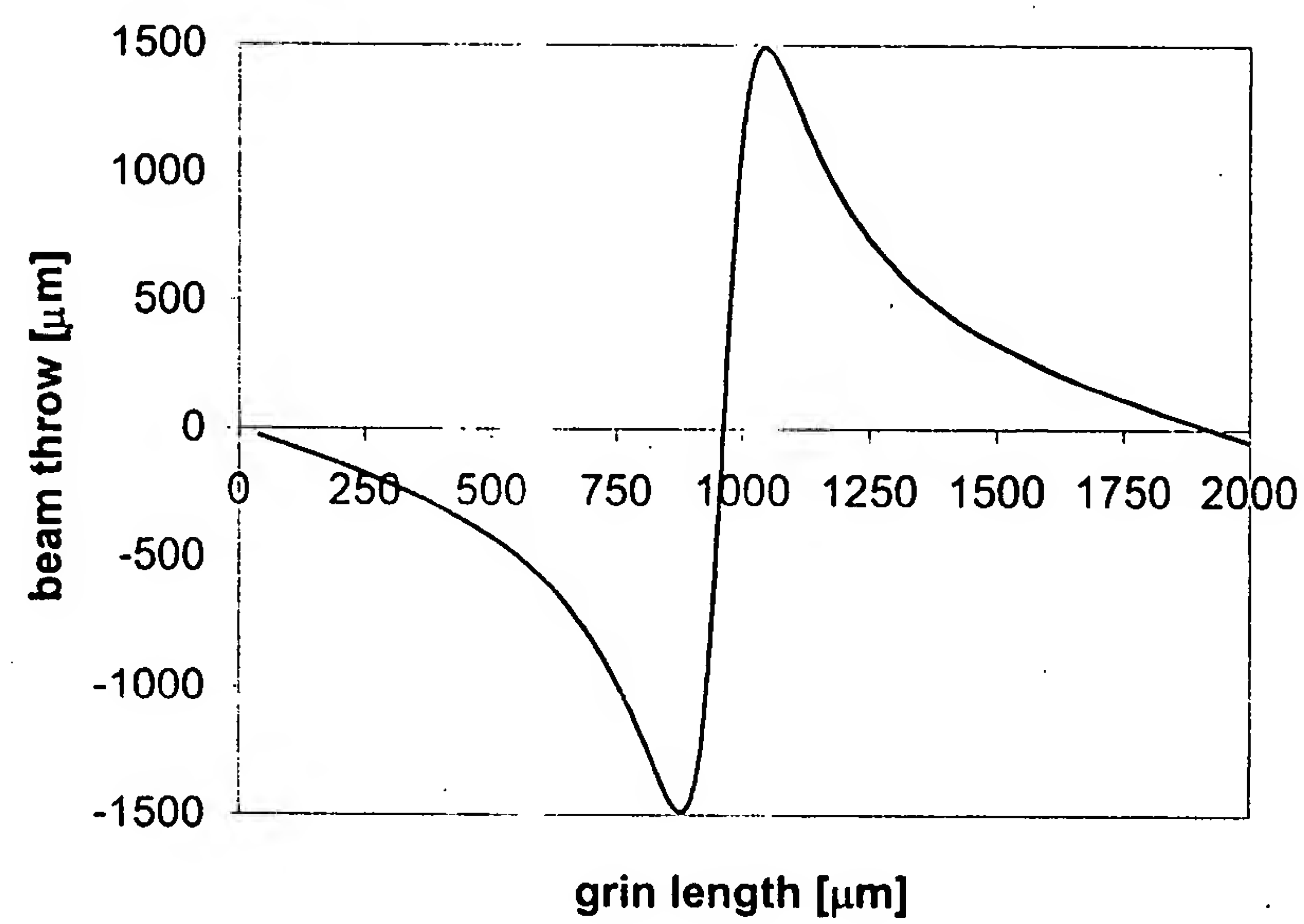



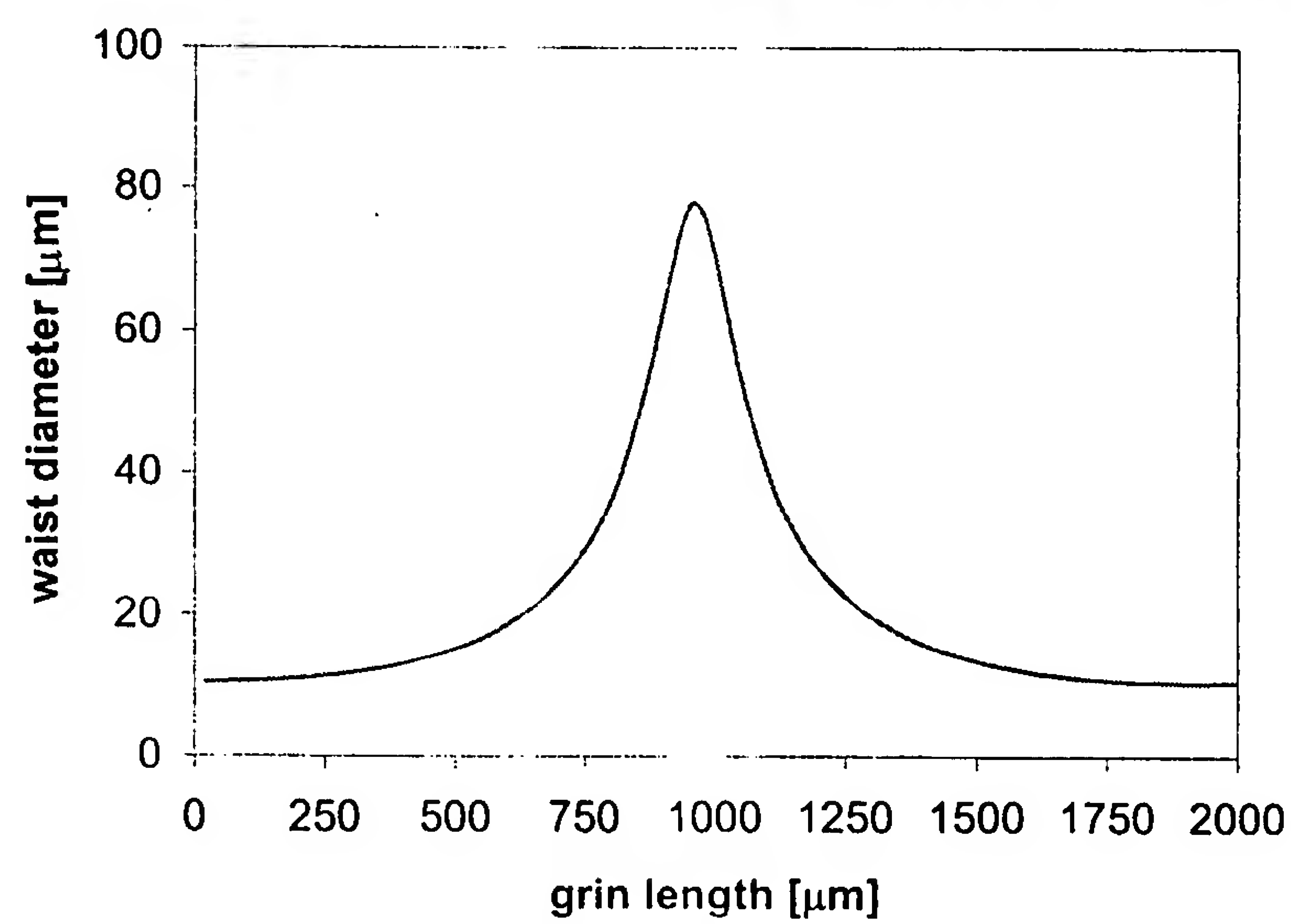
| | | | |
|---|---|---|---|
| 380 | 61.18 | 13.08 | 16.11 |
| 390 | 56.51 | 12.71 | 15.52 |
| 400 | 51.66 | 12.35 | 14.90 |
| 410 | 46.69 | 12.02 | 14.29 |
| 420 | 41.68 | 11.71 | 13.69 |
| 430 | 36.64 | 11.45 | 13.10 |
| 440 | 31.61 | 11.22 | 12.54 |
| 450 | 26.59 | 11.03 | 12.01 |
| 460 | 21.60 | 10.87 | 11.52 |
| 470 | 16.63 | 10.74 | 11.12 |
| 480 | 11.68 | 10.65 | 10.85 |
| 490 | 6.74 | 10.59 | 10.66 |
| 500 | 1.82 | 10.57 | 10.57 |
| 510 | -3.10 | 10.57 | 10.59 |
| 520 | -8.02 | 10.61 | 10.70 |
| 530 | -12.96 | 10.67 | 10.91 |
| 540 | -17.91 | 10.77 | 11.20 |
| 550 | -22.89 | 10.91 | 11.64 |
| 560 | -27.89 | 11.07 | 12.14 |
| 570 | -32.91 | 11.28 | 12.68 |
| 580 | -37.95 | 11.51 | 13.25 |
| 590 | -42.98 | 11.79 | 13.84 |
| 600 | -47.99 | 12.10 | 14.45 |
| 610 | -52.93 | 12.44 | 15.06 |
| 620 | -57.75 | 12.81 | 15.68 |
| 630 | -62.35 | 13.22 | 16.26 |
| 640 | -66.62 | 13.80 | 16.76 |
| 650 | -70.40 | 14.42 | 17.36 |
| 660 | -73.44 | 15.05 | 17.94 |
| 670 | -75.47 | 15.57 | 18.28 |
| 680 | -76.11 | 16.30 | 18.72 |
| 690 | -74.92 | 16.97 | 19.09 |
| 700 | -71.41 | 17.80 | 19.44 |
| 710 | -65.12 | 18.41 | 19.81 |
| 720 | -55.70 | 19.20 | 19.95 |
| 730 | -43.09 | 19.78 | 20.26 |
| 740 | -27.62 | 20.13 | 20.35 |
| 750 | -10.14 | 20.30 | 20.33 |
| 760 | 8.12 | 20.31 | 20.33 |
| 770 | 25.76 | 20.16 | 20.35 |
| 780 | 41.50 | 19.83 | 20.27 |
| 790 | 54.46 | 19.27 | 20.00 |

| | | | |
|---|---|---|---|
| 800 | 64.23 | 18.51 | 19.83 |
| 810 | 70.86 | 17.87 | 19.44 |
| 820 | 74.66 | 17.07 | 19.15 |
| 830 | 76.08 | 16.38 | 18.78 |
| 840 | 75.62 | 15.61 | 18.37 |
| 850 | 73.72 | 15.12 | 17.99 |
| 860 | 70.77 | 14.49 | 17.43 |
| 870 | 67.07 | 13.86 | 16.81 |
| 880 | 62.85 | 13.28 | 16.32 |
| 890 | 58.27 | 12.85 | 15.74 |
| 900 | 53.47 | 12.48 | 15.13 |
| 910 | 48.54 | 12.14 | 14.52 |
| 920 | 43.54 | 11.82 | 13.91 |
| 930 | 38.51 | 11.54 | 13.32 |
| 940 | 33.47 | 11.30 | 12.75 |
| 950 | 28.45 | 11.09 | 12.20 |
| 960 | 23.44 | 10.92 | 11.70 |
| 970 | 18.46 | 10.79 | 11.24 |
| 980 | 13.51 | 10.68 | 10.94 |
| 990 | 8.57 | 10.61 | 10.72 |
| 1000 | 3.64 | 10.57 | 10.59 |

Beam throw (=fiber-to-fiber working distance/2), beam waist (2*w0), and beam width (2*r) at exit of grin lens as a function of grin length:
Beam waist and beam width taken at 1/e2 intensity level, wavelength=1550nm, SMF28 - grin fiber assembly
g = 1.633 mm-1, n0=1.487, NA=0.15, core diam=125 micrometer **(Grin-Rod)**

| grin length [µm] | WD/2 [µm] | 2*w0 [µm] | 2*r [µm] |
|---|---|---|---|
| 20 | -13.21 | 10.57 | 10.82 |
| 40 | -26.44 | 10.59 | 11.71 |
| 60 | -39.73 | 10.62 | 12.96 |
| 80 | -53.10 | 10.65 | 14.54 |
| 100 | -66.57 | 10.71 | 16.30 |
| 120 | -80.19 | 10.77 | 18.38 |
| 140 | -93.97 | 10.84 | 20.39 |
| 160 | -107.95 | 10.93 | 22.46 |
| 180 | -122.16 | 11.03 | 24.70 |
| 200 | -136.64 | 11.14 | 26.94 |
| 220 | -151.42 | 11.27 | 29.17 |
| 240 | -166.55 | 11.42 | 31.39 |
| 260 | -182.06 | 11.57 | 33.59 |
| 280 | -198.01 | 11.75 | 35.77 |
| 300 | -214.44 | 11.95 | 37.92 |
| 320 | -231.41 | 12.16 | 40.05 |
| 340 | -248.98 | 12.39 | 42.14 |
| 360 | -267.22 | 12.65 | 44.20 |
| 380 | -286.21 | 12.93 | 46.22 |
| 400 | -306.03 | 13.24 | 48.19 |
| 420 | -326.78 | 13.58 | 50.13 |
| 440 | -348.56 | 13.95 | 52.01 |
| 460 | -371.49 | 14.35 | 53.85 |
| 480 | -395.71 | 14.80 | 55.64 |
| 500 | -421.37 | 15.28 | 57.37 |
| 520 | -448.66 | 15.82 | 59.05 |
| 540 | -477.79 | 16.42 | 60.66 |
| 560 | -508.97 | 17.07 | 62.22 |
| 580 | -542.50 | 17.80 | 63.70 |
| 600 | -578.69 | 18.62 | 65.12 |
| 620 | -617.89 | 19.52 | 66.47 |
| 640 | -660.55 | 20.54 | 67.74 |
| 660 | -707.14 | 21.69 | 68.92 |
| 680 | -758.23 | 22.99 | 70.01 |
| 700 | -814.43 | 24.47 | 70.99 |
| 720 | -876.44 | 26.17 | 71.84 |
| 740 | -944.94 | 28.11 | 72.53 |



| | | | |
|---|---|---|---|
| 760 | -1020.50 | 30.36 | 73.63 |
| 780 | -1103.40 | 32.96 | 74.58 |
| 800 | -1193.07 | 35.91 | 75.12 |
| 820 | -1287.16 | 39.82 | 75.69 |
| 840 | -1379.54 | 44.52 | 75.96 |
| 860 | -1456.58 | 49.80 | 76.55 |
| 880 | -1490.55 | 55.67 | 76.84 |
| 900 | -1431.05 | 62.63 | 77.34 |
| 920 | -1203.29 | 69.52 | 77.71 |
| 940 | -741.10 | 75.47 | 78.06 |
| 960 | -75.48 | 77.88 | 77.90 |
| 980 | 613.88 | 76.24 | 78.06 |
| 1000 | 1126.63 | 71.06 | 77.75 |
| 1020 | 1399.87 | 64.17 | 77.15 |
| 1040 | 1487.99 | 57.07 | 76.99 |
| 1060 | 1468.60 | 50.88 | 76.70 |
| 1080 | 1397.70 | 45.60 | 76.22 |
| 1100 | 1307.06 | 40.75 | 75.88 |
| 1120 | 1212.64 | 36.65 | 75.16 |
| 1140 | 1121.76 | 33.55 | 74.74 |
| 1160 | 1037.35 | 30.88 | 73.85 |
| 1180 | 960.24 | 28.56 | 72.68 |
| 1200 | 890.30 | 26.55 | 72.00 |
| 1220 | 826.98 | 24.81 | 71.18 |
| 1240 | 769.61 | 23.29 | 70.23 |
| 1260 | 717.50 | 21.95 | 69.16 |
| 1280 | 670.01 | 20.77 | 68.00 |
| 1300 | 626.57 | 19.73 | 66.75 |
| 1320 | 586.67 | 18.80 | 65.41 |
| 1340 | 549.89 | 17.97 | 64.01 |
| 1360 | 515.83 | 17.22 | 62.53 |
| 1380 | 484.17 | 16.55 | 60.99 |
| 1400 | 454.63 | 15.94 | 59.39 |
| 1420 | 426.98 | 15.39 | 57.73 |
| 1440 | 400.98 | 14.89 | 56.01 |
| 1460 | 376.47 | 14.44 | 54.23 |
| 1480 | 353.28 | 14.03 | 52.41 |
| 1500 | 331.27 | 13.65 | 50.53 |
| 1520 | 310.32 | 13.31 | 48.60 |
| 1540 | 290.31 | 12.99 | 46.64 |
| 1560 | 271.16 | 12.71 | 44.62 |
| 1580 | 252.76 | 12.45 | 42.58 |

possible working points for 1x2 design:
- grin length: 1.44 -1.54 mm
- working distance: 802 - 580 micrometer
- waist diameter: 15 - 13 micrometer

possible working points for 2x2 inline design:
- grin length: 1.52 - 1.75mm
- working distance: 620 - 230 micrometer
- waist diameter: 13.3 - 11 micrometer

Largest beam diameter in the Grin rod: 80 micrometer = 64% of Grin diameter,
(we would like to stay below 60%).

| | | | |
|---|---|---|---|
| 1600 | 235.05 | 12.21 | 40.49 |
| 1620 | 217.96 | 11.99 | 38.37 |
| 1640 | 201.42 | 11.79 | 36.22 |
| 1660 | 185.38 | 11.61 | 34.05 |
| 1680 | 169.78 | 11.45 | 31.85 |
| 1700 | 154.57 | 11.30 | 29.64 |
| 1720 | 139.72 | 11.17 | 27.41 |
| 1740 | 125.18 | 11.05 | 25.17 |
| 1760 | 110.92 | 10.95 | 22.93 |
| 1780 | 96.89 | 10.86 | 20.81 |
| 1800 | 83.07 | 10.78 | 18.80 |
| 1820 | 69.43 | 10.72 | 16.74 |
| 1840 | 55.92 | 10.66 | 14.92 |
| 1860 | 42.53 | 10.62 | 13.29 |
| 1880 | 29.23 | 10.59 | 11.94 |
| 1900 | 15.99 | 10.57 | 10.93 |
| 1920 | 2.78 | 10.57 | 10.58 |
| 1940 | -10.43 | 10.57 | 10.73 |
| 1960 | -23.65 | 10.58 | 11.49 |
| 1980 | -36.93 | 10.61 | 12.62 |
| 2000 | -50.27 | 10.65 | 14.14 |

M. Duelli 06/16/00

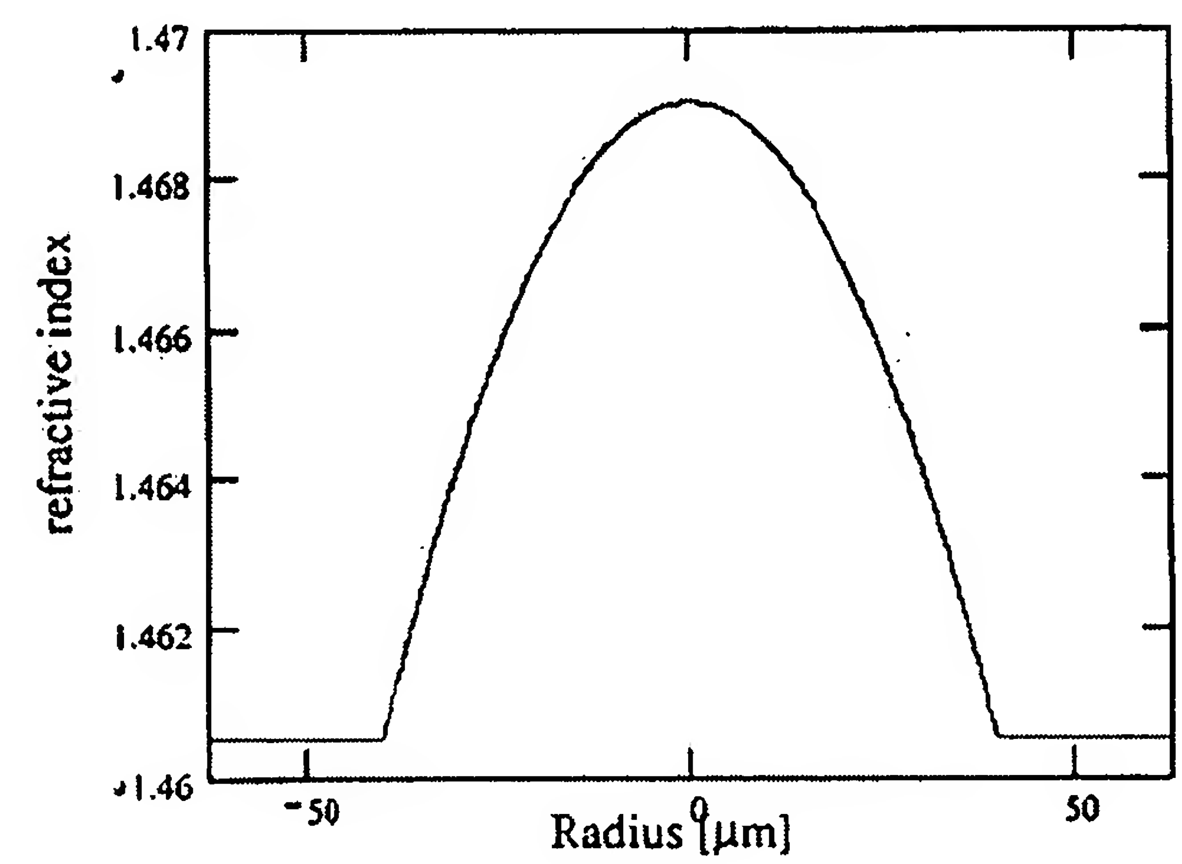
# Specifications for Custom Grin-fiber

The on-axis refractive index has to closely match the refractive index of SMF-28.
SMF-28: $n_{eff} = 1.4682$ at 1550nm

Custom Grin-fiber on axis refractive index: $1.467 < n_0 < 1.47$ at 1550nm

Grin profile:

$$n(r) = n_0\left(1 - \frac{g^2}{2} r^2\right) \qquad g = 2.7\ \text{mm}^{-1}$$




Buffer 250 µm, cladding diameter 125µm, core diameter 80 µm.

... there were some details we discussed!

Technical contact in Germany: Dr. Stein, ext. 166: there is always a 1% dip in the middle (~1μm wide) of a 62.5μm core, but this dip is not measurable with standard instruments. MCVD process

**Andrew Taylor**
07/16/2000 08:40:26 PM

To: MEMS
cc:

Subject: Completion of first round of communication with FiberCore

$n_0 = 1.4815$
$n_{clad} = 1.4729$ $\Big\} \Rightarrow RL = 47\,dB$ $\Downarrow$ measured for standard Grin $= 56\,dB$

Team,

Here are the final comments from FiberCore on the specs we submitted to them:

- NA = 0.16 0.02 (n ~ 9 10-3)
- Undoped cladding (in future they will be able to do this and hit our on axis index spec)
- Ge/P doped core
- Profile spec g = (2.70 0.15)mm-1
- small layer related index variations possible
- small central dip possible

and

- $5/meter, 1 km minimum

An invitation to review the specs we sent, the quote and lead time, and the amount we need to order follows this email.
Regards, Andrew

"BOB SEBESTO" <BOBSEBESTO@prodigy.net> on 07/16/2000 09:06:22 AM

To: Andrew Taylor/Saro/OCLI@OCLI
cc:

Subject: Fw: OCLI Information

---

Andrew:

Attached are our final comments regarding the fiber. These are basically the FCJ specifications. If they are acceptable, please email me your order and we will begin processing it. By the way, we will also need the standard credit references (3 references and a bank) to open your account.

Regards,

Bob Sebesto

- att1.htm

- Comments on OLCI spec.doc

---------------------- Forwarded by Andrew Taylor/Saro/OCLI on 07/16/2000 08:29 PM ---------------------------

"BOB SEBESTO" <BOBSEBESTO@prodigy.net> on 07/11/2000 12:35:41 PM

Grin fiber NA: $NA \simeq n_0 \cdot g \cdot a$

$n_0$ = on axis refractive index
$a$ = core radius
$g$ = grin parameter

$$n^2 = n_0^2 (1 - g^2 r)$$

$$\Rightarrow n \approx n_0 \left(1 - \frac{g^2}{2} r\right)$$

To: Andrew Taylor/Saro/OCLI@OCLI
cc: "Lothar Brehm" <brehm.fcj@t-online.de>

Subject:

---

Andrew:

Following up our recent telephone conversation, to follow is the information regarding the fiber we can provide. This is the closest we can come to your original requirements until our new process is up and running. At that time we may be able to produce the tubes required (fluorine doped) which would give you the on-axis refractive index close to the refractive index of SMF-28.

1.. Maximum refractive index difference between cladding and center of the core of nearly 9*10^-3 is o.k.

2.. Based on undoped cladding material the on-axis refractive index is essentially higher than the refractive index of SMF-28.

Pricing and delivery will be:

Price: $ 5.00/meter
Minimum Order: 1,000 meters
Delivery: 8 - 10 weeks ARO

After review, please let me know if you require any additional information and how you would like to proceed.

Regards,

Bob Sebesto
Director, Sales and Marketing
FiberCore, Inc.

- att1.htm

**Andrew Taylor**
07/11/2000 02:13:16 PM

To: "BOB SEBESTO" <BOBSEBESTO@prodigy.net>
cc: Bob Hallock/Saro/OCLI@OCLI, Markus Duelli/Saro/OCLI@OCLI

Subject: Re: Fiber Specifications 7/11/00

Bob,

Thank you for the technical feedback, pricing and lead time information regarding the requested set of fiber specifications. Based on your email below, we have modified our original specs to not match the on-axis SMF-28 index. I understand that FiberCore may be able to match the on-axis SMF-28 index when your newly patented process to make depressed tubes in-house becomes available. Until then, we would like to get fiber drawn with the following specs (see attachment below for printable version):

**Optical Specifications**
g = 2.70 +/- 0.01 mm^-1
On-axis refractive index to match as closely as possible that of SMF-28 fiber (see attachment for index profile)

**Dimensional Specifications**
Core Diameter: 80 micron ± 2 micron
Cladding Diameter: 125 micron ± 1 micron
Core-Clad Concentricity: < 2 micron
Cladding Non-circularity < 2%
Core Non-circularity < 5%
Coating Geometry: 245 micron ± 5 micron
Fiber Length: > 10 m lengths

**Mechanical Specifications**
Proof Test: 0.7 GPa
Standard Duel Coating Draw

FiberCore Specifications_

Please let me know if we need to make any additional modifications, or if I can issue a PO.
Best Regards, Andrew

OCLI Proprietary

"BOB SEBESTO" <BOBSEBESTO@prodigy.net> on 07/11/2000 12:35:41 PM

"BOB SEBESTO" <BOBSEBESTO@prodigy.net> on 07/11/2000 12:35:41 PM

To: Andrew Taylor/Saro/OCLI@OCLI
cc: "Lothar Brehm" <brehm.fcj@t-online.de>

Subject:

---

Andrew:

Following up our recent telephone conversation, to follow is the information regarding

the fiber we can provide. This is the closest we can come to your original requirements until our new process is up and running. At that time we may be able to produce the tubes required (fluorine doped) which would give you the on-axis refractive index close to the refractive index of SMF-28.

1.. Maximum refractive index difference between cladding and center of the core of nearly 9*10^-3 is o.k.

2.. Based on undoped cladding material the on-axis refractive index is essentially higher than the refractive index of SMF-28.

Pricing and delivery will be:

Price: $ 5.00/meter
Minimum Order: 1,000 meters
Delivery: 8 - 10 weeks ARO

After review, please let me know if you require any additional information and how you would like to proceed.

Regards,

Bob Sebesto
Director, Sales and Marketing
FiberCore, Inc.

- att1.htm

**Andrew Taylor**
07/11/2000 11:07:51 AM

To: Bob Hallock/Saro/OCLI@OCLI, Markus Duelli/Saro/OCLI@OCLI, Don Friedrich/Saro/OCLI@OCLI, Bryant Hichwa/Corporate/OCLI@OCLI
cc:

Subject: FiberCore Update with cost and lead times

Team,

Below is the correspondence to date we have had with Robert Sebesto of FiberCore. In the most recent email below he indicates they can/will draw fiber for us:
1) Adjustments on index profile we asked for that causes a $\Delta n$ on axis (the supply of depressed clad tubes appears to be limited)
2) $5 a meter, 1 km minimum
3) 8-10 week lead time

We can do 1 of 3 things:
1) Buy as is.....
2) Re-send GRIN profile without asking for a depressed index cladding, but matched on axis
3) Look for a different supplier (only other company I am aware of that will do custom orders was SSOC, Spectran Specialty Optics Corporation, which is now owned by Lucent and thus may not be willing to do such small orders these days; I do have a contact inside which I have not pursued in Mike O'Connor at (860) 678-6534)

I recommend we try #2 above ASAP. Additionally, we should keep our correspondence going with Sebesto for future business as he believes they will be able to do our original GRIN profile with their newly patented process (which comes online in a few months) using a F doped cladding. Please keep in mind this chunk of business is small potatoes for FiberCore (or any other fiber manufacturer). Robert indicated to me they will do 12 million in sales this year with another 20 million on the books that they don't have the capacity for......
Regards, Andrew

---------------------- Forwarded by Andrew Taylor/Saro/OCLI on 07/11/2000 10:34 AM ---------------------------

"BOB SEBESTO" <BOBSEBESTO@prodigy.net> on 07/11/2000 12:35:41 PM

To: Andrew Taylor/Saro/OCLI@OCLI
cc: "Lothar Brehm" <brehm.fcj@t-online.de>

Subject:

---

Andrew:

Following up our recent telephone conversation, to follow is the information regarding the fiber we can provide. This is the closest we can come to your original requirements until our new process is up and running. At that time we may be able to produce the tubes required (fluorine doped) which would give you the on-axis refractive index close to the refractive index of SMF-28.

1.. Maximum refractive index difference between cladding and center of the core of nearly 9*10^-3 is o.k.

2.. Based on undoped cladding material the on-axis refractive index is essentially higher than the refractive index of SMF-28.

Pricing and delivery will be:

Price: $ 5.00/meter
Minimum Order: 1,000 meters
Delivery: 8 - 10 weeks ARO

After review, please let me know if you require any additional information and how you would like to proceed.

Regards,

Bob Sebesto
Director, Sales and Marketing
FiberCore, Inc.

---------------------- Forwarded by Andrew Taylor/Saro/OCLI on 07/11/2000 10:36 AM ---------------------------

"BOB SEBESTO" <BOBSEBESTO@prodigy.net> on 06/27/2000 11:29:18 PM

To: Andrew Taylor/Saro/OCLI@OCLI
cc: "Dr. Wolfgang Haemmerle" <haemmerle@fibercore.de>, "Lothar Brehm" <brehm.fc@t-online.de>

Subject: Re: Custom preform/fiber for OCLI

---

Andrew:

I am traveling with our V.P. of Operations this week and I will review the new specification with him tomorrow and let you know if any additional changes need to be made or discussed.

Regards,

Bob Sebesto

----- Original Message -----
From: Andrew Taylor
To: BOB SEBESTO
Cc: Chuck DeLuca ; Lothar Brehm ; haemmerle@fibercore.de ; John Olson ; Bob Hallock
Sent: Tuesday, June 27, 2000 4:28 PM
Subject: Re: Custom preform/fiber for OCLI

Robert,

The attached information is considered OCLI propietary and is submitted pursuant to the NDA between OCLI and FiberCore, Inc. dated 6/15/00. Please review the latest set of specifications (given in the FiberCore Specifications_1.doc below) and communicate back to us:

1) What specs can/can ,t be met; please suggest changes to specs which can be met when possible to do so

2) Please provide us with an estimation of cost; formal RFQ not necessary at this time

3) Please provide us with estimated lead times

Please contact me directly at (707) 525-7177 if you have any questions.

Best Regards, Andrew

(See attached file: FiberCore FAX3.doc)(See attached file: FiberCore Specifications_1.doc)

PS I also sent you a 2 page eFax with the aforementioned information:

"BOB SEBESTO" <BOBSEBESTO@prodigy.net> on 06/24/2000 09:22:32 PM

To: Andrew Taylor/Saro/OCLI@OCLI
cc: "Chuck DeLuca" <FBCE2CDL@aol.com>, "Lothar Brehm" <brehm.fcj@t-online.de>

Subject: Fw: Special preform/fiber for Olli

Andrew:

To follow is the response from our plant regarding the special preform you requested. As discussed, we may be able to produce the required tubes with our new process, but this would not be available until late this year. If you would like to make any changes to your requirements which could possibly enable us to provide preforms, please let me know and I will pass it on to the right people.

In the interim, if you would like a copy of our standard multimode preform specification, please advise and I will fax it to you.

Sincerely,

Bob Sebesto
Director, Sales and Marketing
FiberCore, Inc.

----- Original Message -----
From: Wolfgang Haemmerle
To: Charles DeLuca
Cc: Mohd Aslami
Sent: Monday, June 19, 2000 8:52 AM
Subject: Special preform/fiber for Olli

I see the following problem for making such a special fiber:
  a.. based on the sent picture the needed index difference for the graded index profile is nearly 9*10^-3
  b.. the core/clad index difference for the SMF-28 is nearly 4.5*10^-3 (standard SMF with only Ge doped core and undoped cladding, index difference core/clad nearly 4.5*10^-3 ).
  c.. that means the cladding should have for the special GRIN fiber a negative index difference of (9*10^-3 - 4.5*10^-3 - 4.5*10^-3=0).
  d.. such a high index depression of -4.5*10^-3 is impossible to make with Standard-MCVD, if possible with a improved MCVD only a grave with a narrow width

can be made.
e.. such low index substrate tubes are at this time not available (only F-320 with a index difference of -1.2*10^-3).
f.. no tolerances are known for the profile parameters, the core diameter, the index difference

In the meantime it would be desireable to get the unknown tolerances for the different GRIN-fiber parameters.
Best Regards,
Wolfgang Haemmerle

--
Research & Development
Tel: +49-3641-610 160
Fax: +49-3641-610 101
email: haemmerle@fibercore.de
FiberCore Jena GmbH

- att1.htm

# FiberCore Jena GmbH

**INFOGLAS**

Göschwitzer Str. 20, 07745 Jena
Tel.: 49 - 3641 / 6 10 140
Fax : 49 - 3641 / 6 10 101

E-Mail: pinter@fibercore.de


| | | | |
|---|---|---|---|
| Fax: | **001 707 525 7846** | Date: | **15.09.00** |
| To: | **Optical Coating Laboratory, Inc.**<br>**Santa Rosa / USA** | From: | **Hans-Freimut Pinter**<br>**Sales** |
| Attn.: | **Mrs. Lee Anne Seaman** | Copy: | **Bob Sebesto** |
| Ref: | **Dispatch details** | Pages: | **1 + 1** |

Dear Mrs. Seaman,

we would like to announce the dispatch of one box with optical fiber in accordance with your **PO 109002** dated 07/19/2000 by FEDEX today. Please refer to the following tracking No.:

**8214 0439 9191**

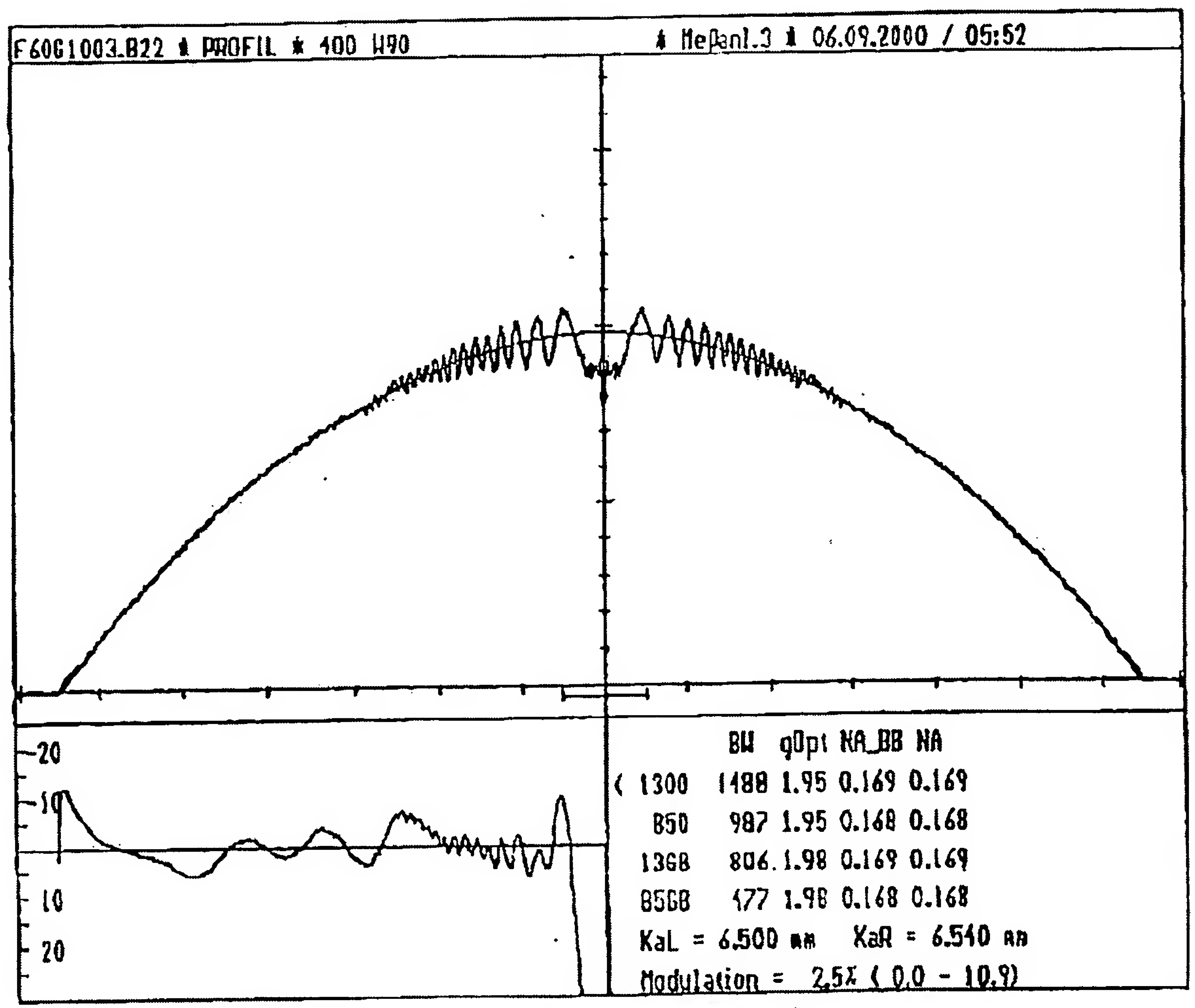
Please find the characterization data of the used preform together with the fiber refractive index profile enclosed.

We thank you very much for the order, hope to continue our technical and commercial relation.

Best regards

Pinter

Hans-Freimut Pinter
Sales


F60G1003.B22 * PROFIL * 400 W90
* MeBanl.3 * 06.09.2000 / 05:52
-20
-10
10
20
BW qOpt NA_BB NA
( 1300 1488 1.95 0.169 0.169
850 987 1.95 0.168 0.168
1368 806 1.98 0.169 0.169
8568 477 1.98 0.168 0.168
KaL = 6.500 mm XaR = 6.540 mm
Modulation = 2.5% ( 0.0 - 10.9)

OPTICAL COUPLING

- BUILD TWO SAMPLES: w/ PUSH '2' = 21μm (SIMILAR TO PART 1)

  I.L. = −0.52 dB

  ONE FIBER FIT
  ONE " DID NOT FIT.

- NEXT TWO SAMPLES (2 = 21μm PUSH)

  I.L. = −0.77 dB

  (BAD LOOKING SPLICE)



Work continued from Page

## SHORT STRIP LENGTH SPLICE

→ NO TOOLING AT THIS POINT, TRY & PROVE THAT A TOTAL STRIP LENGTH OF ~5mm IS POSSIBLE.

| | SPLICE | IL | LENGTH | |
|---|---|---|---|---|
| | 1 | −.07 | 3.5 mm | 2 PUSH = 23μm |
| | 2 | −.04 | 3.6 mm | |
| | 3 | −.07 | 3.5 mm | 2 PUSH = 21μm |
| HAVING TROUBLE w/ CLEAVES | 4 | −.21 | 3.5 mm | |
| | 5 | −.30 | 3.5 | |
| | 6 | −.01 | 3.7 mm | |
| | 7 | −0.00 | 3.5 mm | |
| | 8 | −0.00 | 3.6 mm | |
| | 9 | | | |
| | 10 | | | |
| | 11 | | | |
| | 12 | | | |



Work continued to Page

SIGNATURE DATE

DISCLOSED TO AND UNDERSTOOD BY DATE WITNESS DATE

SHORT SPLICE w/ 900μm

→ 900μm WILL NOT FIT THRU S.S. SPLICER CLAMP GUIDE. TRY REMOVING.

↳ DOES NOT WORK



Work continued from Page

SHORT SPLICE CONT

MADE 4 OPTICAL SAMPLES:

-0.68 IN SPLICER
-0.70 IN 5 AXIS → ALIGNMENT 1st PAIR: -1.2 dB HIGH

-0.90 dB 5 AXIS → ALIGNMENT 2nd PAIR:

→ PROGRAM MAYBE AN ISSUE. THIS WAS A SM PROGRAM USED FOR MULTIMODE. REALLY SHOULD USE MM PROGRAM & MODIFY TO GET SHORT STRIP LENGTH

INDICATES AN ANGLE ON END OF FIBER(S)



Work continued to Page

SIGNATURE DATE 7/31/00

DISCLOSED TO AND UNDERSTOOD BY DATE WITNESS DATE

PROJECT NO. 19889

TITLE Spot Size Measurement

BOOK NO. 1130

Work continued from Page

3/4 pitch CMMF - SMF, 80 $\mu m$ core, optics

| Fiber # | GRIN length | # fringes | $D_2$ | $D_1$ | S | Beam radius at waist ~~Spot Size~~ |
|---|---|---|---|---|---|---|
| #6 | 2076 | 0 | 2520 | 1061 | 10 | 6.76 |
| | | | 2600 | 1019 | 10 | 6.24 |
| | | | 2590 | 1030 | 10 | 6.33 |
| Average: | | | 2570 | 1036.667 | 10 | 6.44 |

stddev $D_2$ = $\Delta w_1$ = 21.78 $\mu m$

stddev $D_1$ = $\Delta w_2$ = 43.59 $\mu m$

$\Delta S$ = 50 $\mu m$

$\therefore$ spot size = 12.87 $\mu m$ $\pm$ 1.16 $\mu m$

| Fiber # | GRIN length | # fringes | $D_2$ | $D_1$ | S | Beam radius at waist |
|---|---|---|---|---|---|---|
| #7 | 2102 | 1 | 3247 | 1406 | 10 | 5.36 |
| | | | 3277 | 1414 | 10 | 5.30 |
| | | | 3296 | 1419 | 10 | 5.26 |
| | | | 3273.33 | 1413 | 10 | 5.30 |

$\Delta w_2$ = 6.56 $\mu m$

$\Delta w_1$ = 24.70 $\mu m$

$\Delta S$ = 50 $\mu m$

$\therefore$ spot size = 10.61 $\mu m$ $\pm$ 0.41 $\mu m$

~ continued on next page ~

Work continued to Page 30

SIGNATURE Andrew Taylor

DATE 9/21/00

DISCLOSED TO AND UNDERSTOOD BY

DATE

WITNESS

DATE

OCLI

PROJECT NO. 19889

TITLE Spot Size Measurement BOOK NO. 1130

Work continued from Page 29

| Fiber # | GRIN Length | # fringes | $D_2$ | $D_1$ | s | Beam radius at waist |
|---|---|---|---|---|---|---|
| # 8 | 2158 um | 2 | 4261 | 2335 | 10 | 5.12 |
| | | | 4334 | 2332 | 10 | 4.93 |
| | | | 4345 | 2317 | 10 | 4.87 |
| | | | 4313.33 | 2328 | 10 | 4.97 |

$\Delta w_1$ = 9.64 um $\Delta s$ = 50 um

$\Delta w_2$ = 45.65 um

∴ spot size = 9.94 um ± 0.60 um

| Fiber # | GRIN Length | # fringes | $D_2$ | $D_1$ | s | Beam radius at waist |
|---|---|---|---|---|---|---|
| # 9 | 2185 um | 1 | 3833 | 1889 | 10 | 5.08 |
| | | | 3834 | 1899 | 10 | 5.10 |
| | | | 3872 | 1897 | 10 | 5.00 |
| | | | 3846.33 | 1895 | 10 | 5.06 |

$\Delta w_1$ = 5.29, $\Delta w_2$ = 23.23, $\Delta s$ = 50 um

∴ spot size = 10.11 um ± 0.34 um

recentered beam

| Fiber # | GRIN Length | # fringes | | $D_2$ | $D_1$ | s | Beam radius at waist |
|---|---|---|---|---|---|---|---|
| # 10 | 1930 um | 1 | ~~2654~~ | 2723 | 1308 | 10 | 6.97 |
| | | | ~~2678~~ | 2713 | 1316 | 10 | 7.06 |
| | | | | 2704 | 1299 | 10 | 7.02 |
| | | | | 2713.33 | 1307.667 | 10 | 7.02 |

$\Delta w_1$ = 8.50 um $\Delta w_2$ = 9.50 um, $\Delta s$ = 50 um

∴ spot size = 14.04 um ± 0.43 um

~ continued on next page ~

SCIENTIFIC NOTEBOOK PRODUCTIONS CHICAGO

Work continued to Page 31

SIGNATURE Andrew Taylor DATE 9/21/00

DISCLOSED TO AND UNDERSTOOD BY DATE WITNESS DATE

# OCLI



PROJECT NO. 19889

TITLE Spot Size Measurement BOOK NO. 1130

Work continued from Page 30

| Fiber # | GRIN Length | # fringes | $D_2$ | $D_1$ | S | Beam radius at waist (um) |
|---|---|---|---|---|---|---|
| 11 | 1938 | 0 | 1724 | 598 | 8 | 7.01 |
| | | | 1693 | 620 | 8 | 7.36 |
| | | | 1704 | 605 | 8 | 7.18 |
| | | | 1707 | 607.667 | 8 | 7.18 |

$\Delta w_1 = 11.24$, $\Delta w_2 = 15.72$, $\Delta S = 50$ um

spot size = 14.36 um ± 0.79 um

*Note: due to small $D_1$ MFD, remeasuring #11

| | | | | | | |
|---|---|---|---|---|---|---|
| 11 | 1938 | 0 | 2280 | 996 | 10 | 7.69 |
| | | | 2263 | 984 | 10 | 7.72 |
| | | | 2273 | 1003 | 10 | 7.77 |
| | | | 2272 | 994.33 | 10 | 7.72 |

$\Delta w_1 = 9.61$, $\Delta w_2 = 8.54$, $\Delta S = 50$ um

spot size = 15.44 um ± 0.52 um

| | | | | | | |
|---|---|---|---|---|---|---|
| #12 | 1934 | 2 | 3058 | 1846 | 10 | 8.14 |
| | | | 3060 | 1810 | 10 | 7.89 |
| | | | 3070 | 1824 | 10 | 7.92 |
| | | | 3062.67 | 1826.67 | 10 | |

$\Delta w_1 = 18.15$, $\Delta w_2 = 6.43$, $\Delta S = 50$ um

spot size = 15.97 um ± 0.71 um

*Note: Beam had a funny shape

Work continued to Page 32

SIGNATURE Andrew Taylor DATE 9/21/00

READ AND UNDERSTOOD BY DATE WITNESS DATE

| TYPE (CLEAVE SIDE) | LENGTH | QUALITY |
|---|---|---|
| SMF / CMMF (1ST ANNEAL ATTEMPT) | ~850 | BAD (?)  |

→ SPLICE, MOVE SPLICE SO CMMF BETWEEN ELECTRODES, LOW POWER ARC, CLEAVE

TITLE

PROJECT NO.

BOOK NO.



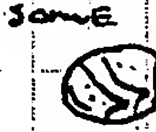
ZERO OFF

Work continued from Page

CMMF CLEAVING

STANDARD CMMF SPLICED/CLEAVE 

↑ CLEAVE POINT

| TYPE (CLEAVE SIDE) | LENGTH (μm) | QUALITY | |
|---|---|---|---|
| SMF / CMMF | 780, 850 | BAD |  |
| SMF / CMMF | 350 | GOOD | |
| SMF / CMMF | ~1200 | GOOD | |
| SMF / SMF | ANY LENGTH | GOOD | |
| SMF / MMF | 350 | GOOD | |
| SMF / MMF | ~850 | GOOD | |
| CMMF / CMMF | ~850 | BAD |  |
| CMMF / SMF | ~850 | RANDOM | BAD  OTHER  |
| SMF / CMMF (NO BUMP) | ~850 | BAD | SAME STANDARD |
| SMF / CMMF (NO PULL) | ~850 | BAD | |
| SMF / CMMF HIGH POWER UP TO 130 & 5000ms | ~850 | BAD | → STANDARD |
| SMF / CMMF LOWER POWER DOWN TO 50 & 750ms | ~850 | BAD | SOME STANDARD SOME DIFFERENT  (DEFINITE DEFLECTION OF FRINGE @ CORE INTERFACE) |
| SMF / CMMF LOW TENSION DOWN TO 160 grs. | ~850 | BAD | STANDARD |
| SMF / CMMF HIGH TENSION UP TO 300 grs | ~850 | BAD | STANDARD |

Work continued to Page 30



SIGNATURE DATE

DISCLOSED TO AND UNDERSTOOD BY DATE WITNESS DATE 9/25/00

Work continued from Page

ANNEAL PROCESS MODIFICATIONS

9/28/00 - 1st ATTEMPT MANUAL MOTION (NO SPECIFIC LENGTH OF MOTION), USED 2nd PROGRAM TO RUN LOW POWER ARC. CLEAVED.

→ RESULTED IN DIFFERENT CLEAVE SURFACE. NOT GOOD BUT IMPROVED. STANDARD CLEAVE: 

THIS CLEAVE: 

10/5/00 - 2nd ATTEMPT

- SET FIBER ~~CLAMP~~ JAWS IN SPLICE TO MOVE 600 μm. HAD TO RELEASE OPPOSITE JAW TO ALLOW MOVEMENT.
- SWITCHED TO SECOND PROGRAM AFTER PROGRAM PAUSE & JAW MOVEMENT.
- 2nd PROGRAM FOR LOW POWER ANNEAL ARC.

→ RESULTED IN 'GOOD' QUALITY FLAT CLEAVE.

10/6/00

- INSTEAD OF 2nd PROGRAM FOR ANNEAL, CUMBERSOME FOR OPERATOR, CAN WE USE MULTIPLE CLEANING ARCS.
- RAISE CLEANING TIME FROM 200 ms TO 600 ms. NOT TOO MUCH CLEANING POWER, BUT WON'T NEED TO USE EXCESSIVE MULTIPLE CLEANING ARCS FOR ANNEAL.
- 5 ARCS REQUIRED TO GIVE ENOUGH ANNEALING FOR GOOD CLEAVE.



Work continued to Page 66

SIGNATURE Robert Black DATE 11/13/00

DISCLOSED TO AND UNDERSTOOD BY Andrew T. Taylor DATE 11/14/00 WITNESS DATE

CONTINUED FROM PAGE 65

10/6/00 CONT

SETTINGS:

| | |
|---|---|
| ARC POWER | 53 |
| DURATION | 2150 |
| PUSH DISTANCE | 21 |
| CLEANING ARC | 600 |
| ARC POWER OFFSET | 0 |
| PULL START TIME | 1500 |
| PULL DISTANCE | 20 |

ISSUES: • WHEN MOVING FIBER FOR ANNEAL, IF FIBER DOES NOT RESEAT THE SAME WAY INTO ALIGNMENT V-GROOVES, THE RESULTING LATERAL OFFSET STRESS GETS ANNEALED OUT OF THE FIBER. THIS RESULTS IN A PERMANENT KINK IN THE FIBER.

→ SOLUTION: ULTRASONICALLY CLEAN BOTH FIBER PARTS BEFORE PLACING IN SPLICER. DEBRIS ON FIBER SLIDES THRU V GROOVE AND INTERFERES W/ RESEATING OF FIBER

10/18/00 • CAN REDUCE # OF ANNEAL ARCS REQUIRED BY INCREASING LENGTH OF CLEANING ARC & REDUCING ARC POWER

INITIAL PROGRAM: # ANNEALS: 5, POWER: 50, TIME 600 ms

2ND PROGRAM: POWER: 25, TIME: 1000, # ANNEALS: 4

3RD: POWER: 10, TIME: 2000 ms, # ANNEALS: 2

ALL RESULT IN QUALITY CLEAVES.

ISSUES: • PROGRAM DOES NOT SELF ADJUST TO ACCOMODATE WEAR AND/OR REPLACEMENT OF THE ELECTRODES.

→ SOLUTION: SET UP A FUSION SPLICER PROGRAM TO OPERATE OFF AN ARC CHECK. THIS PROGRAM WOULD ACCOMODATE ELECTRODE WEAR. PERFORM ARC CHECK ON DAILY BASES.

CONTINUED TO PAGE 66

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TITLE

BOOK NO.



Work continued from Page 66

10/30/00 ARC CHECK PROGRAM → REFER TO PAGES 48-51

SETTINGS:

| | |
|---|---|
| ARC POWER : | 35* |
| PRE-FUSE TIME : | 240 ms |
| ARC DURATION : | 2150 ms |
| Z PUSH DISTANCE : | 21 μm |
| ARC POWER COMPENSATION: | 65 |
| CLEANING POWER OFFSET: | 0 |
| CLEANING TIME : | 1000 ms |
| Z PULL START TIME : | 1500 ms |
| Z PULL DISTANCE : | 20 μm |
| AUTO ADDITIONAL ARC: | 0 |
| REPEAT ARC TIMES: | 1 |
| REPEAT ARC DURATION: | 0 |
| REPEAT ARC INTERVAL: | 5000 ms |
| REPEAT ARC POWER OFFSET: | 0 |
| CLEAVE ANGLE : | 2° |
| LOSS LIMIT : | 0.2 dB |
| ALIGNING TYPE : | CLAD |
| MODE FIELD RADIUS LEFT: | 4.75 μm |
| MODE FIELD RADIUS RIGHT: | 35.05 μm |
| – TENSION : | 200 g |
| – # OF ANNEALS : | 4 |

RESULTS IN GOOD QUALITY OPTICS

→ FLOW CHART OF PROCESS PAGE 68

SCIENTIFIC BINDERY PRODUCTIONS CHICAGO 60605 MADE IN USA

Work continued to Page 68

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## Optical Sub-Assembly Flow Chart

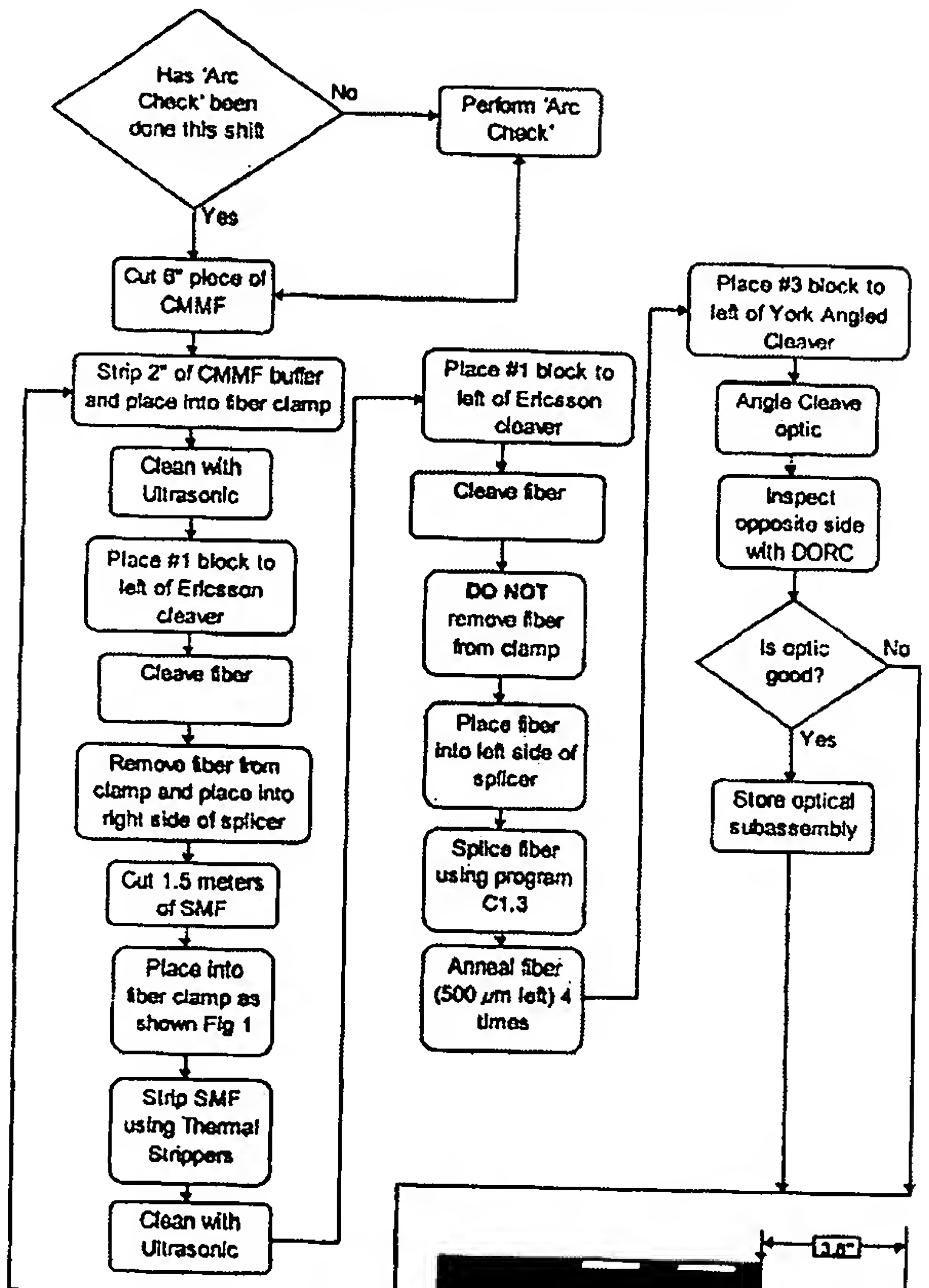



Fig-1

# TITLE

PROJECT NO.
BOOK NO.



Work continued from Page

ANGLED OPTICS
→ 20 FRINGE TARGET

| ID | LENGTH | # FRINGES | TIME | COMMENT |
|---|---|---|---|---|
| 1 | | 21 | 4:50 | |
| 2 | | ~~23~~ 19 | ~~5:50~~ 420 | |
| REBUILD AFTER * | CUT OFF 1MM LENGTH BEFORE CLEAVE | | | |
| 3 | | 18 | 6:08 | FAILED MM CLEAVE TWICE |
| → * 4 | | 21 | 5:00 | FAILED MM CLEAVE |
| 5 ~~**~~ REBUILD | | ~~14~~ 19 | 4:18 | LONG LENGTH CMMF USED. |
| 6 | | 17 | | |
| 7 | | | | |
| 8 | | | | |
| 9 | | | | |
| 10 | | | | |
| 11 | | | | |
| 12 | | | | |

* CONCERNED ON VARIATION OF FRINGE COUNT. CHECK ANGLE → 1 MM & 2 MM ALL 20 FRINGES. IS IT STRAIN LENGTH OF 1MM PAST BLADE ?



** ~~TAPED~~ TIGHTENED LOCK SCREWS FOR TORSION AMOUNT. DID THIS CHANGE AMOUNT OF TORSION ?

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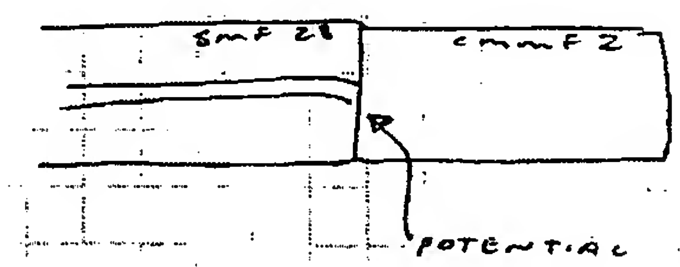
CMMF2 SPLICE KINK




AS SEEN ON SPLICER

SEEN w/ CMMF2 BUT NOT CMMF1

POSSIBLE PROGRAMS

#1
5μm PUSH
0μm PULL
100ms PREFUSE

→ LOOKED BETTER THEN STANDARD PROGRAM BUT NOT AS GOOD AS CMMF1

→ GOOD CLEAVE

#2
3μm PUSH
0 PULL
100ms PREFUSE

→ STILL EXHIBITED PROBLEM, ALSO NECKED DOWN @ SPLICE JOINT

#3
3μm PUSH
0 PULL
70ms PREFUSE

→ SAME PROBLEM, LESS NECKING DOWN @ JOINT

#4
1μm PUSH
0 PULL
50 PREFUSE

→ KINK LOOKED GOOD BUT NECKED @ JOINT

* DUE TO LOAD ERROR CMMF CLEANED TWICE EXCESSIVE ROUNDING. ~~REPEAT~~



Work continued to Page

SIGNATURE

DATE 1/2/01

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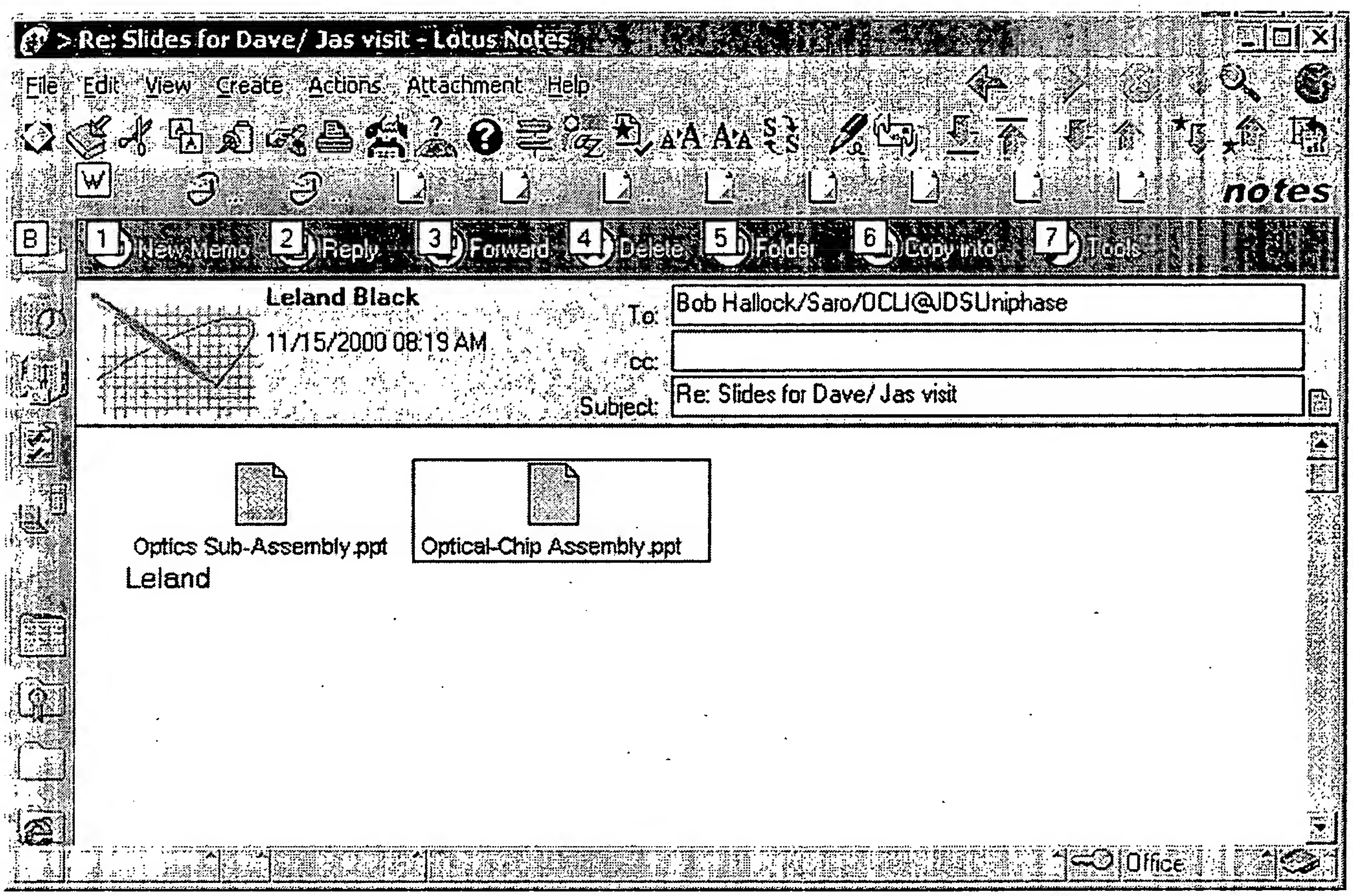


> Re: Slides for Dave/ Jas visit - Lotus Notes

File Edit View Create Actions Attachment Help

1 New Memo 2 Reply 3 Forward 4 Delete 5 Folder 6 Copy into 7 Tools

**Leland Black**
11/15/2000 08:19 AM

To: Bob Hallock/Saro/OCLI@JDSUniphase
cc:
Subject: Re: Slides for Dave/ Jas visit

Optics Sub-Assembly.ppt
Optical-Chip Assembly.ppt

Leland

Office

JDS Uniphase

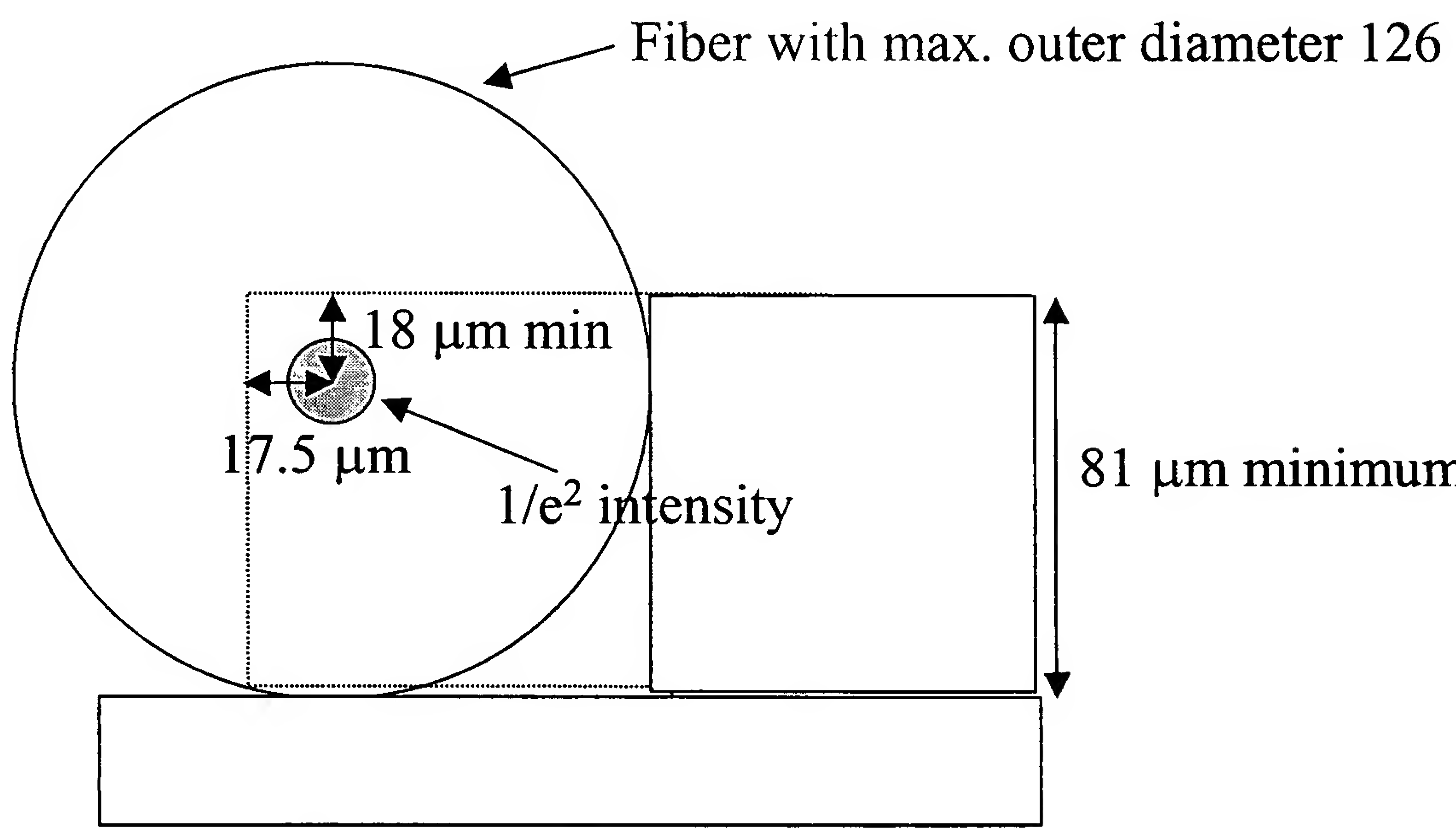
# MEMS Optical Sub-Assembly

## Manufacturing Process and Optical Performance

# Beam Size Limitation

Electrostatic MEMS mirror actuator

- Mirror movement: 35 µm
- Minimum fiber trench depth: 81 µm

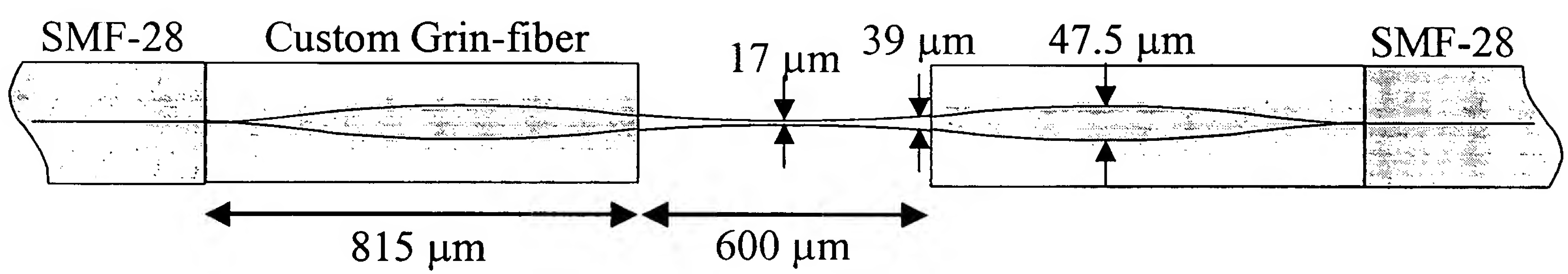



For excess loss <0.05dB mirror diameter has to be larger than 3.54 x beam waist
$\Rightarrow$ maximum projected beam waist at mirror ($1/e^2$-intensity radius) = 9.9 µm

# Optics Solution

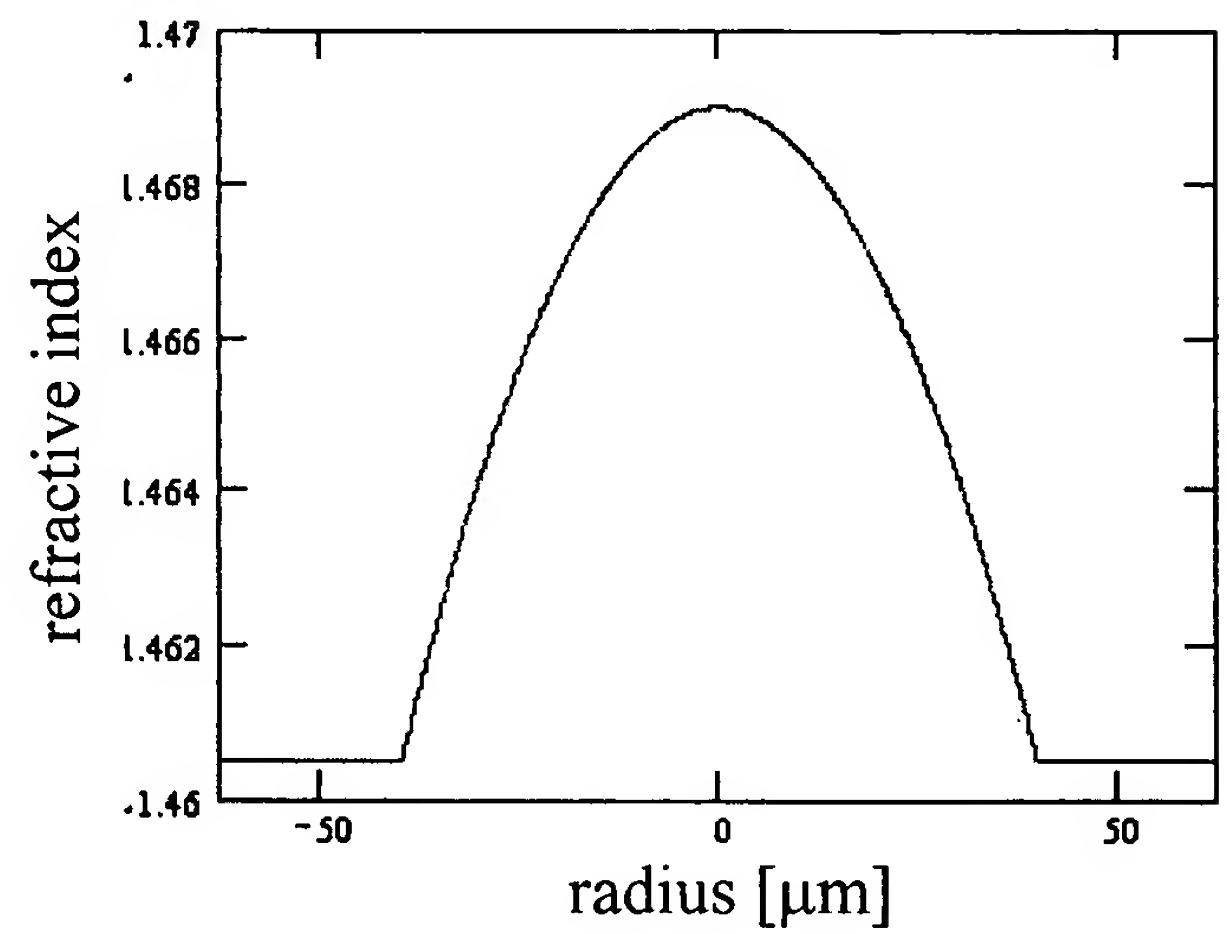
## Single mode fiber - custom Grin fiber assembly

(30 degree angle between fibers)



# Optics Solution - Con't

Gradient index profile:



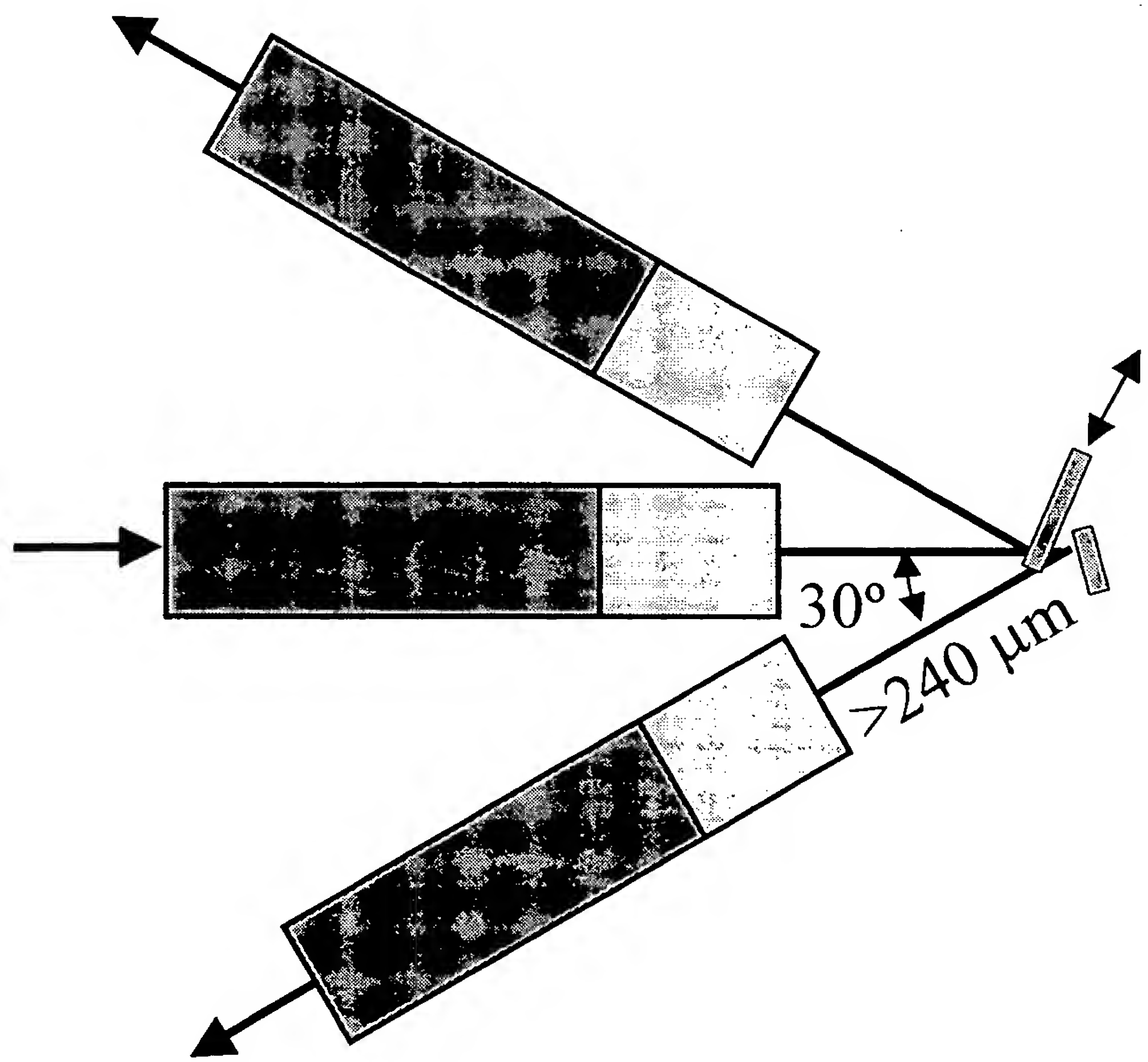

$$n(r) := n_0\left(1 - \frac{g^2}{2}\cdot r^2\right)$$

$g = 2.7\ \mathrm{mm}^{-1}$
$n_0 = 1.469$ (@ $\lambda$=1.55μm)

Return loss (4 degree angle cleave): 76 dB without AR
82 dB with 1% AR

# *Fiber-to-Fiber Working Distance*

(30 degree angle between fibers)

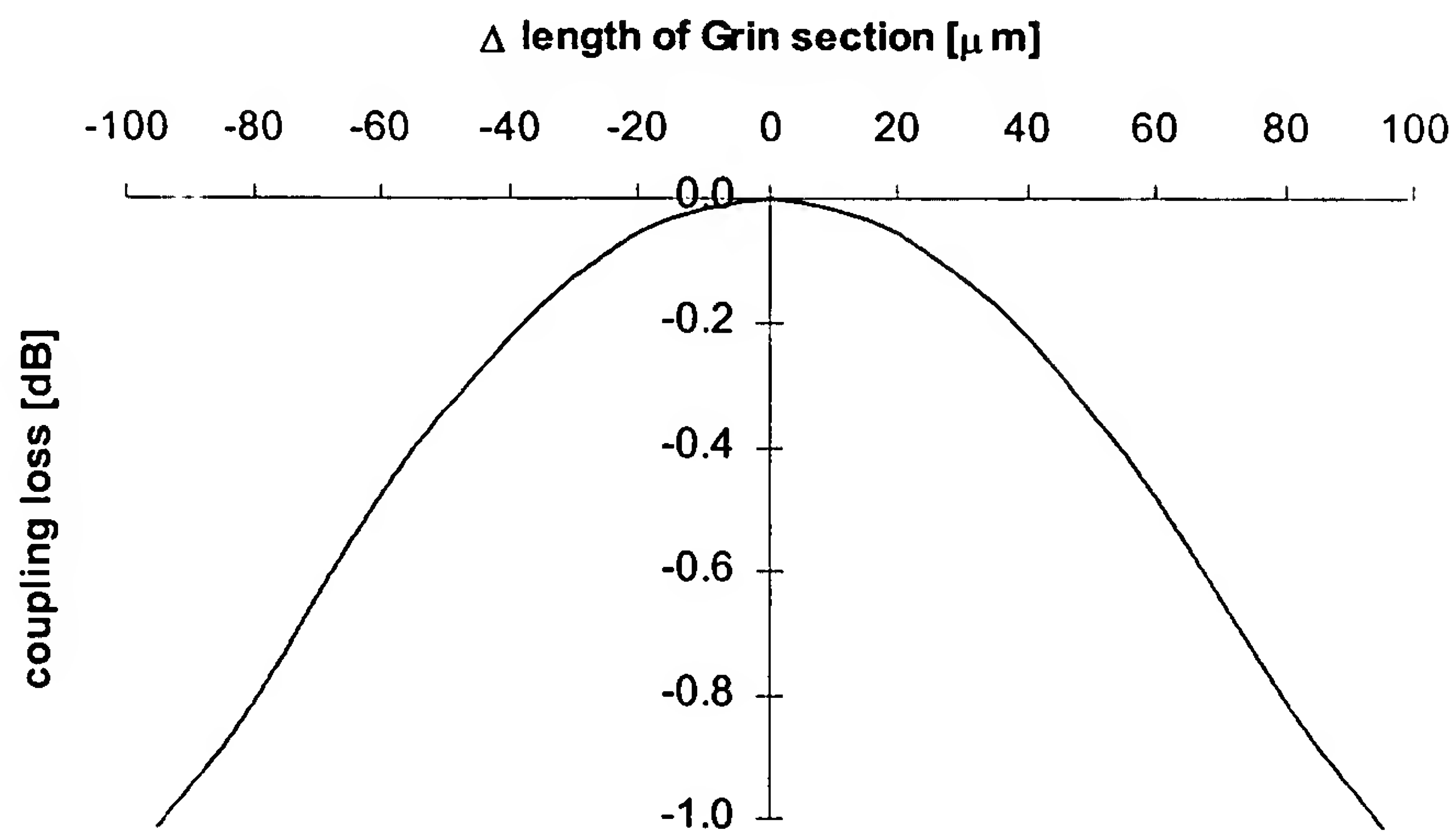


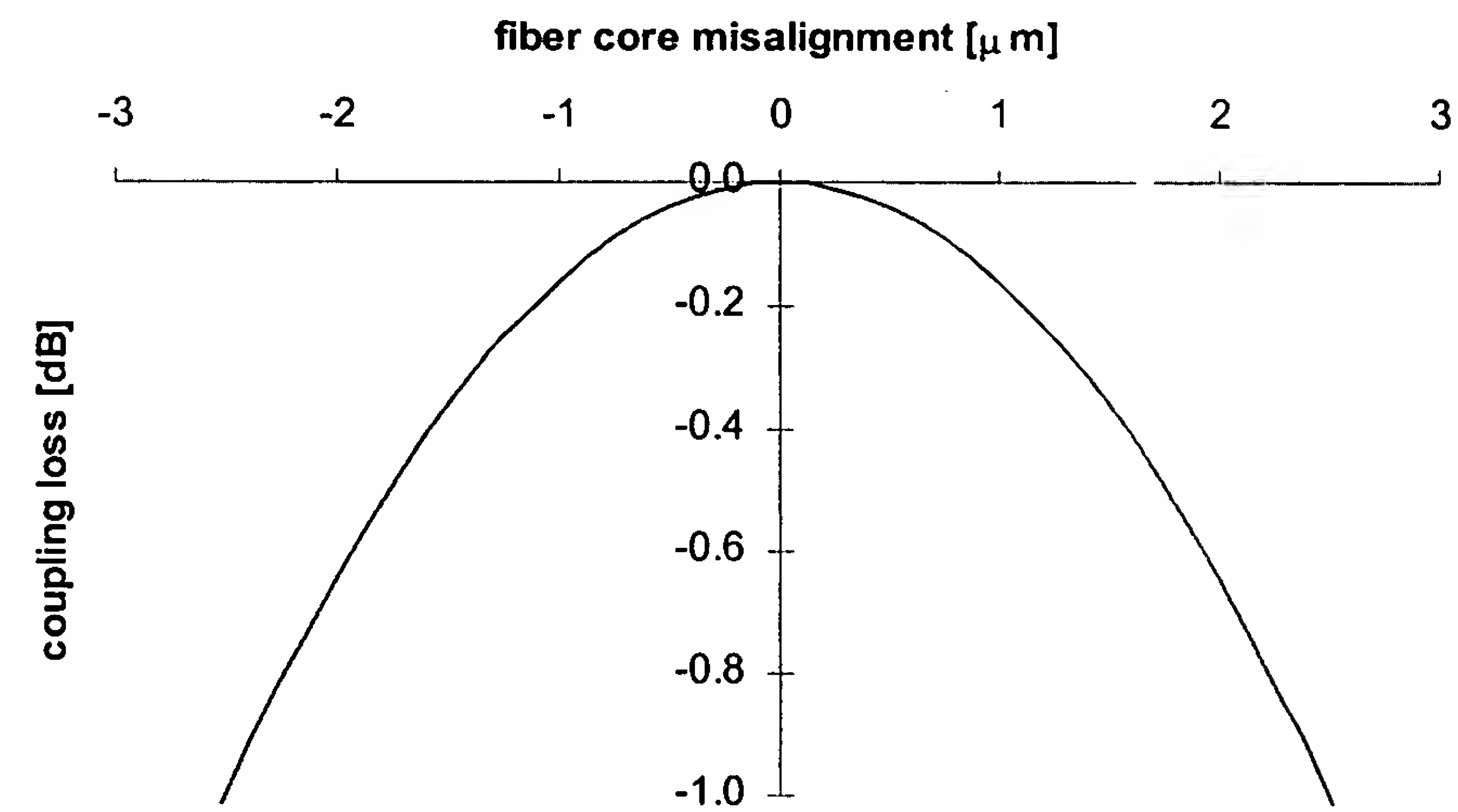

126 μm diameter fibers touch at a working distance of 480 μm

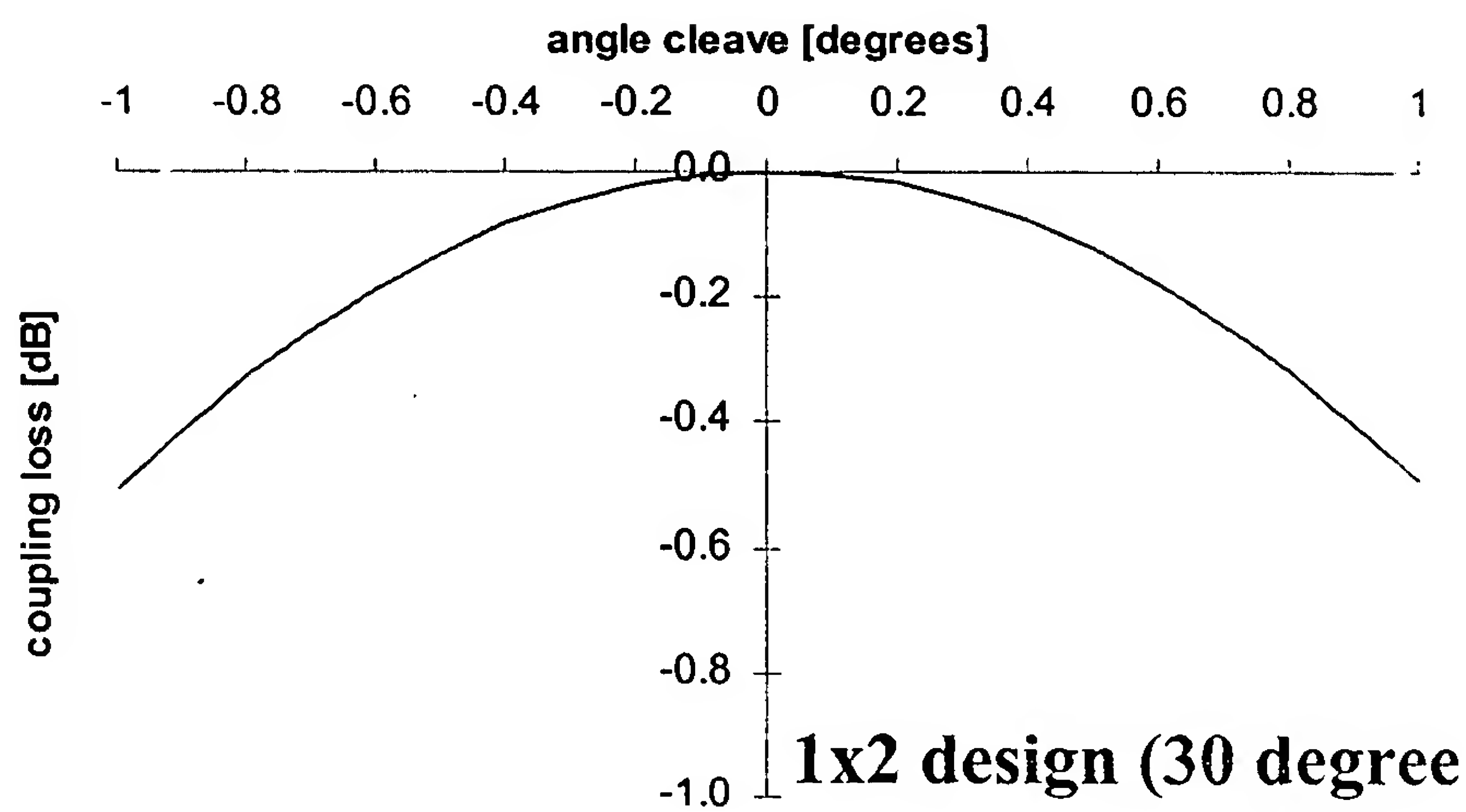
⇒ fiber -to-fiber working distance >480 μm

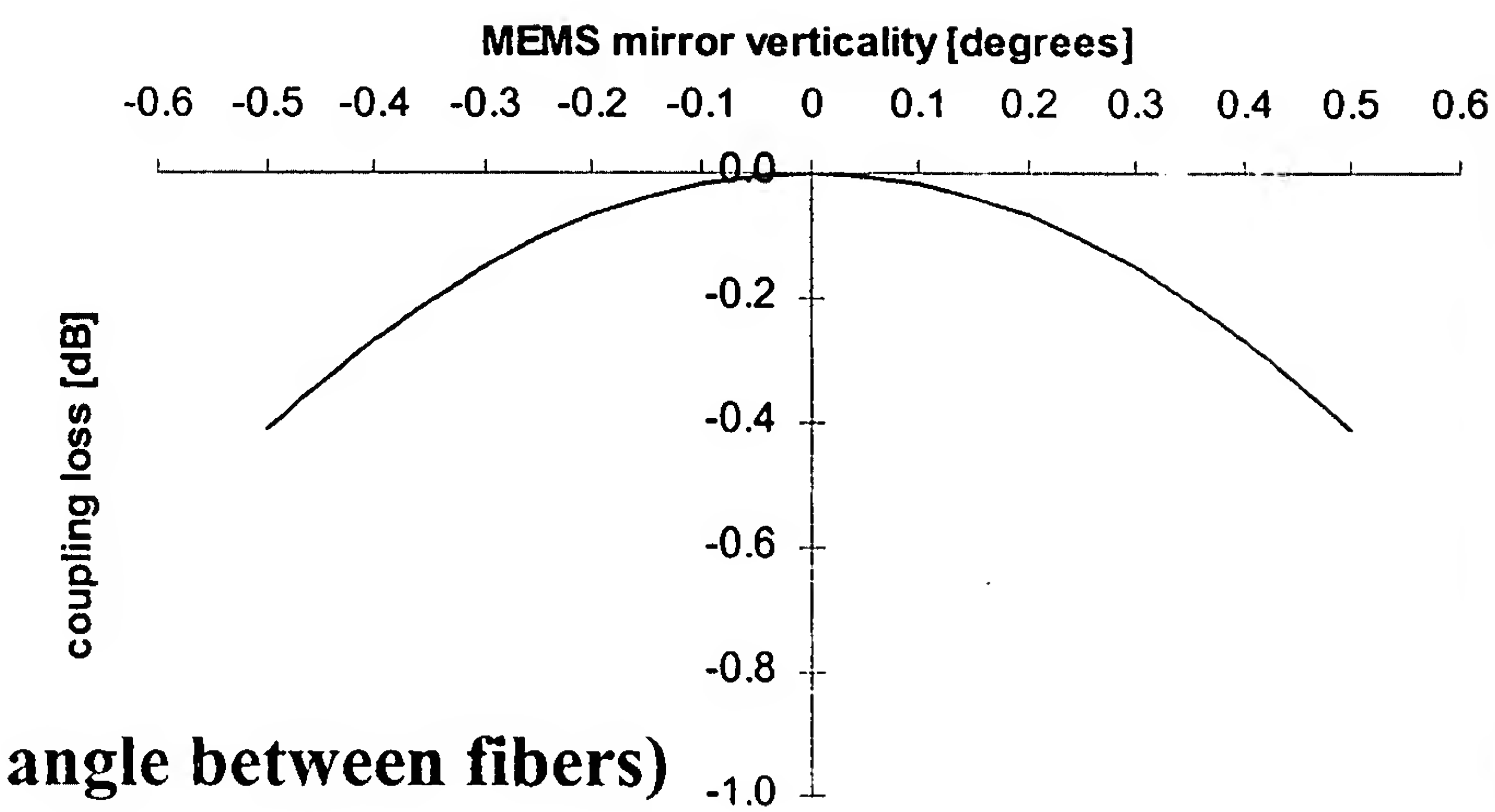
# Fabrication Tolerances

## (30 degree angle between fibers) Single mode fiber - custom Grin fiber assembly




**1x2 design (30 degree angle between fibers)**

*MEMS Product Development*

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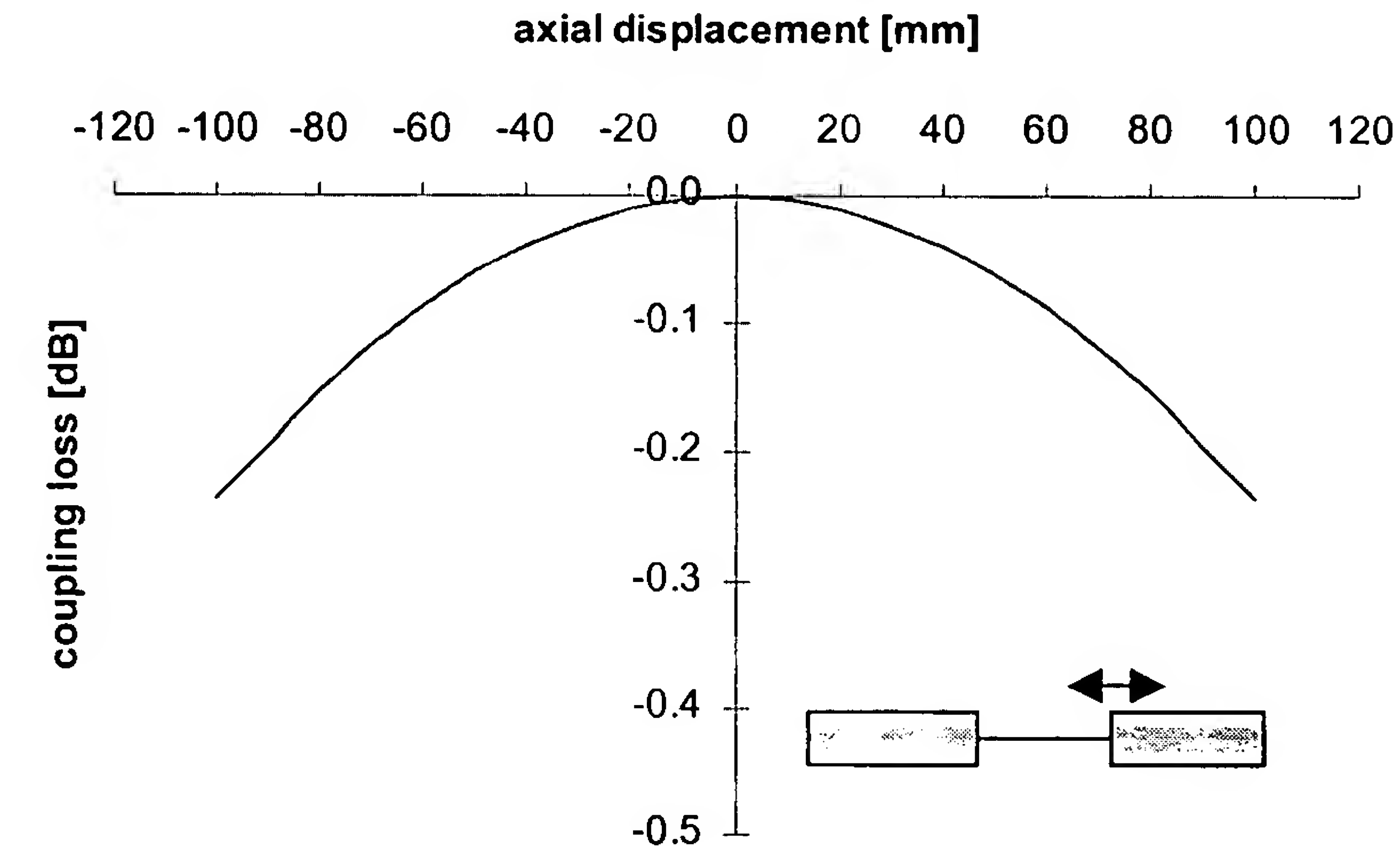
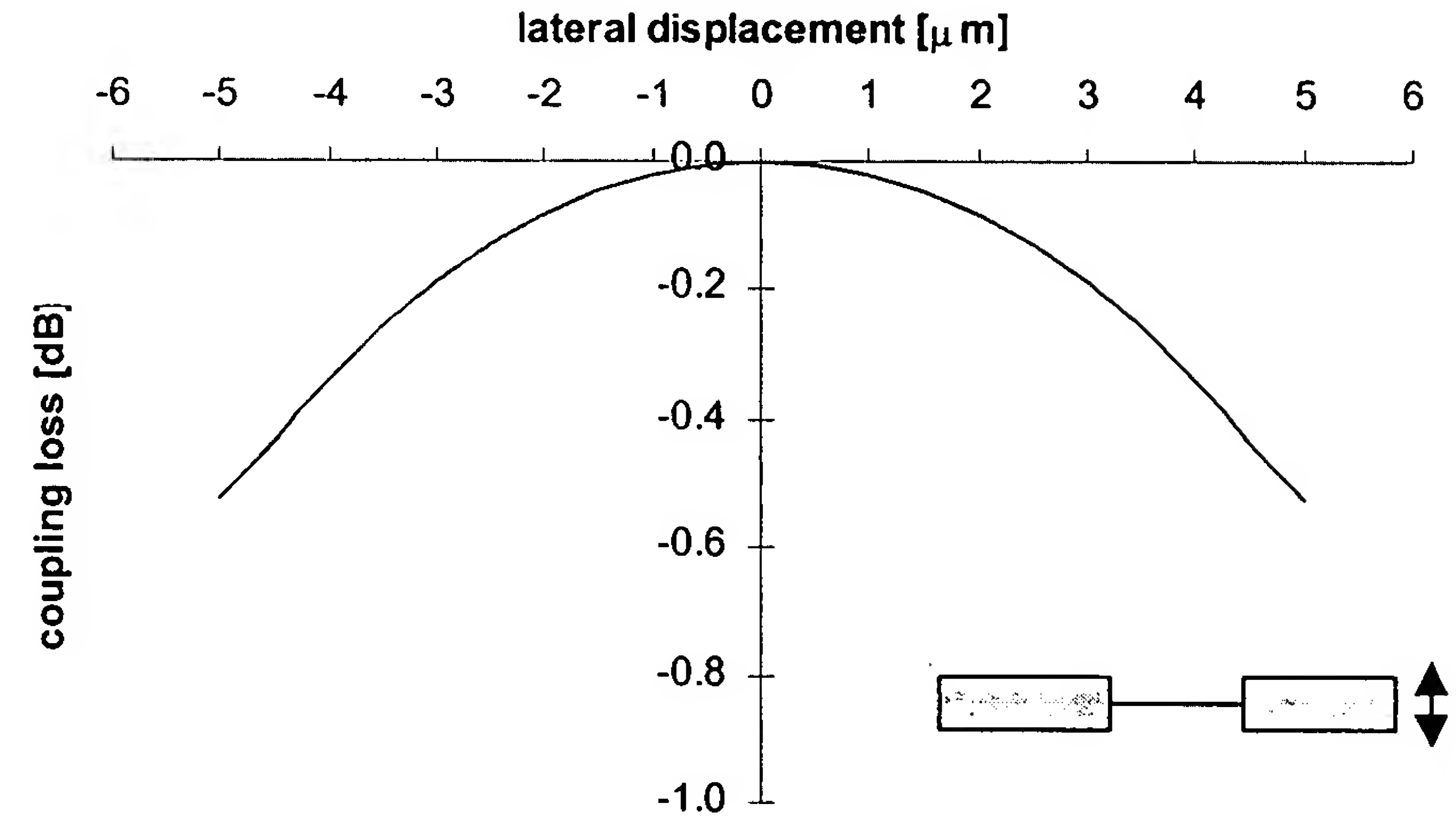
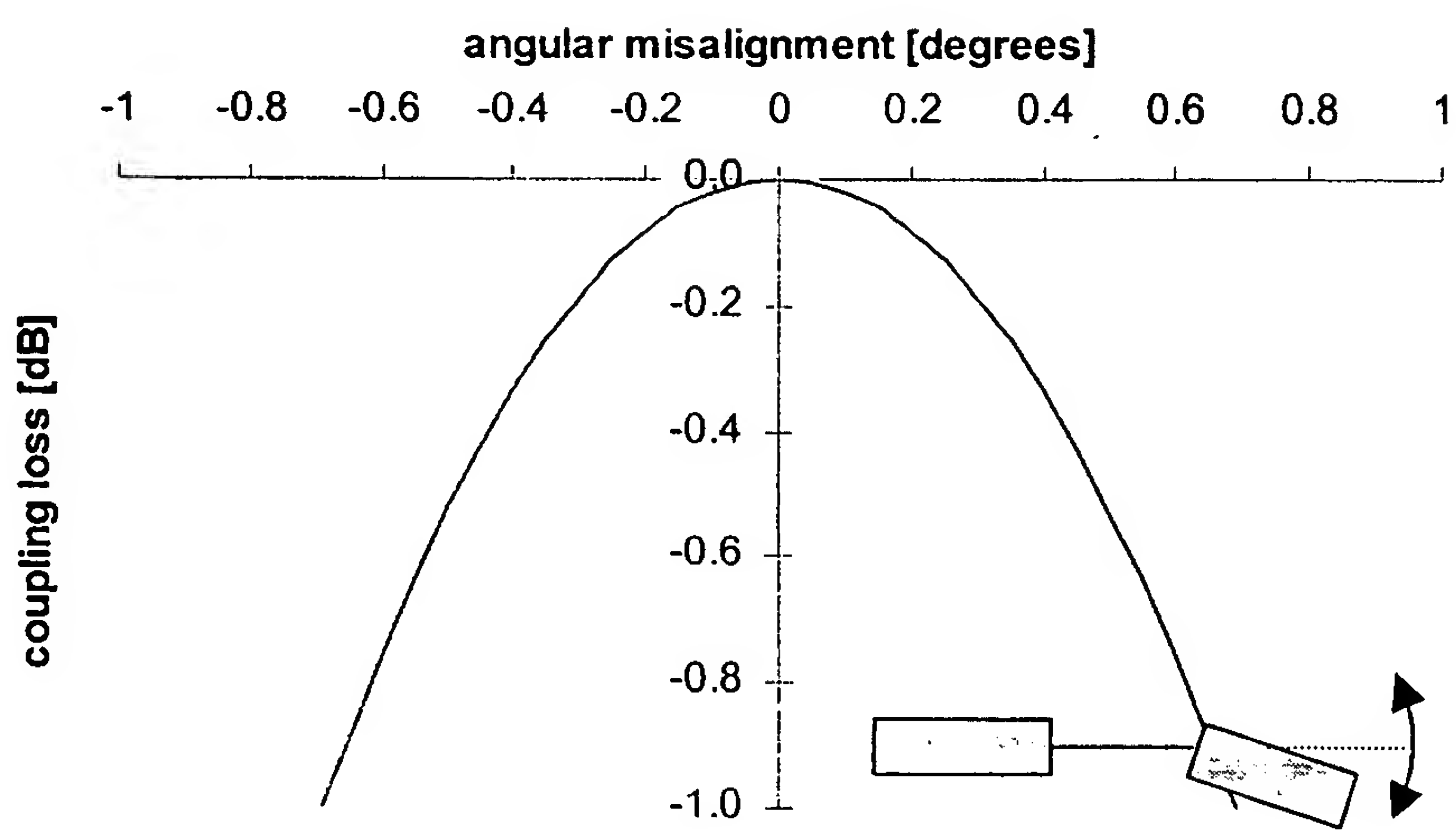
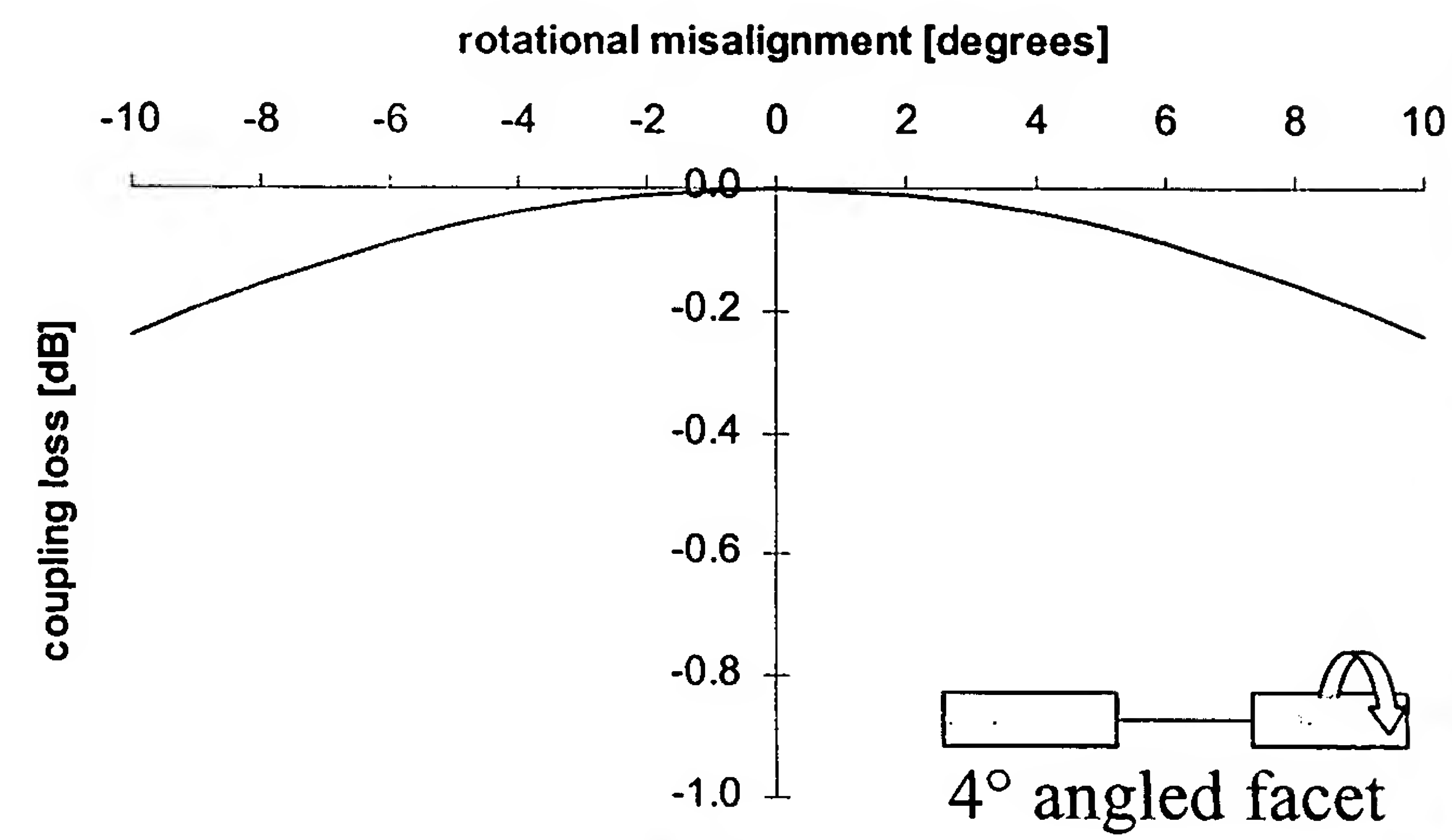
# Alignment Tolerances

## (30 degree angle between fibers) Single mode fiber - custom Grin fiber assembly

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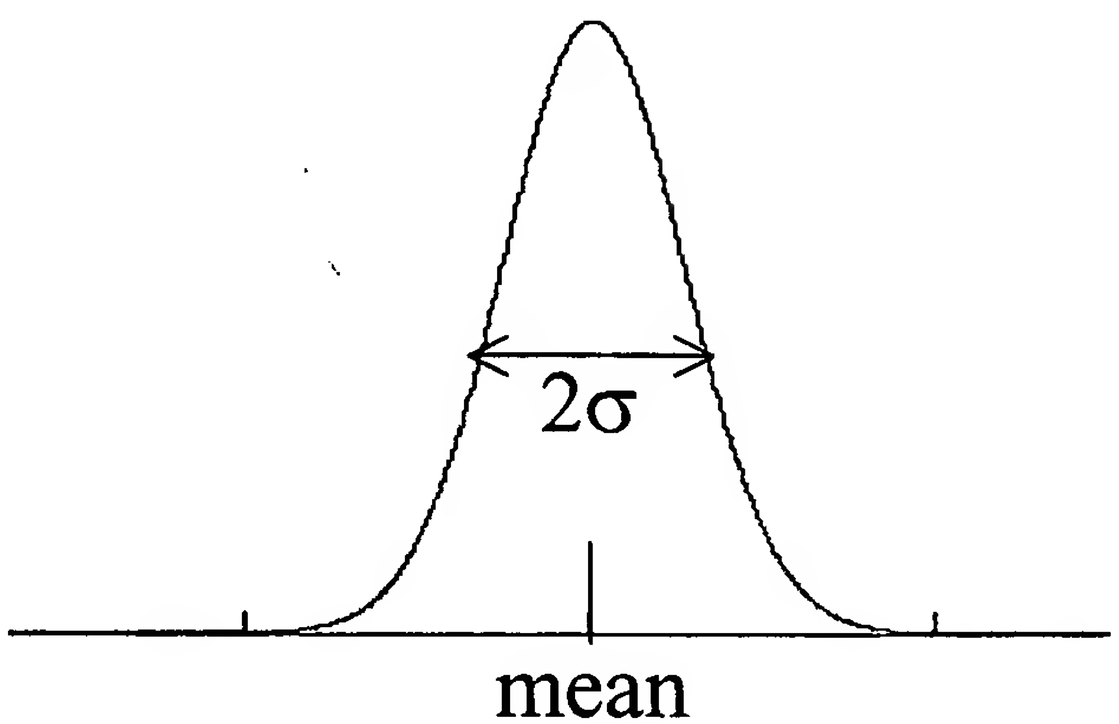
# Loss Budget Calculations

Assumptions:

1) Errors (lateral, axial misalignment, mirror verticality,…) are normally distributed
2) Errors are independent

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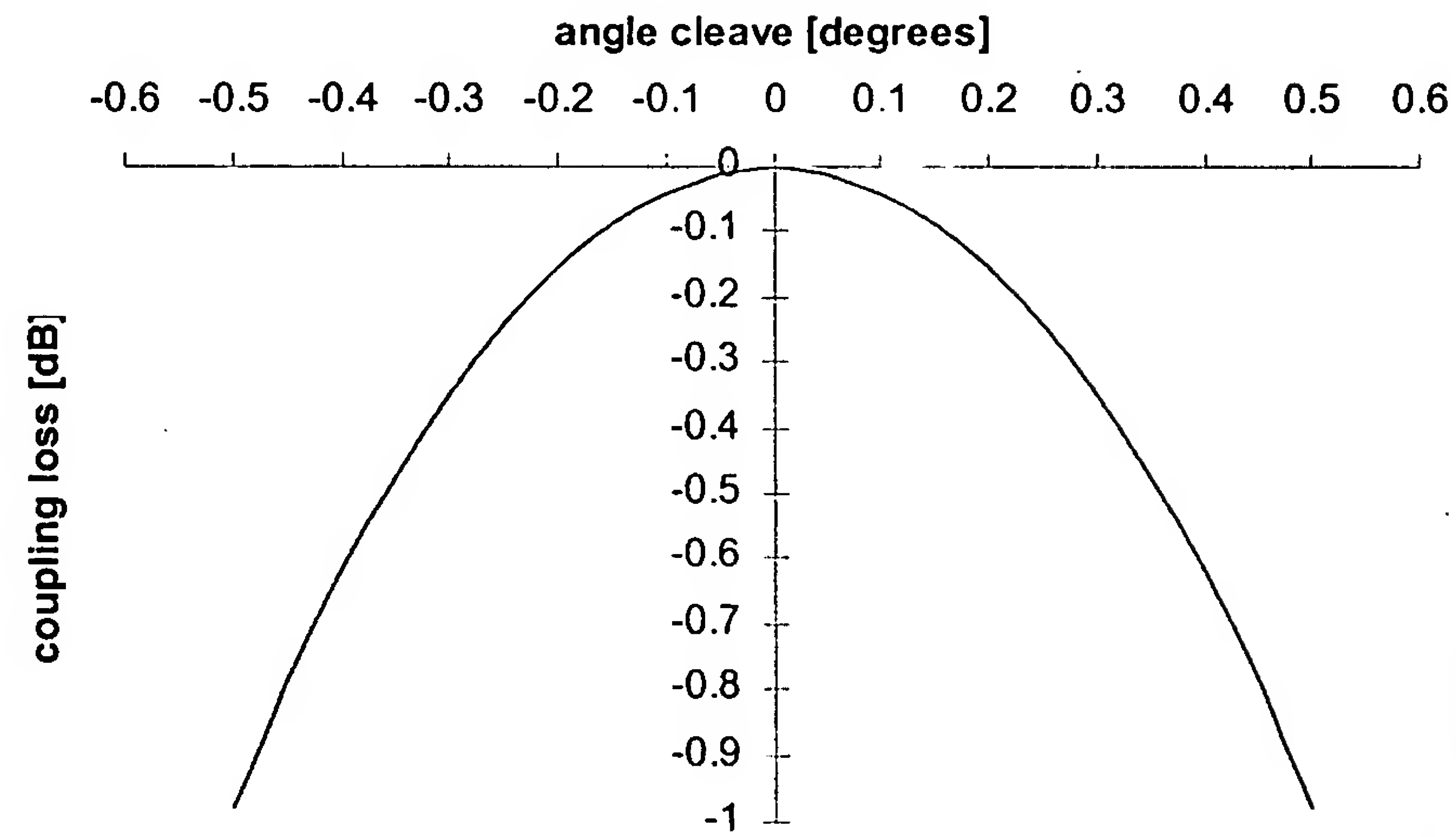



$\Rightarrow$ **distribution of insertion loss with standard deviations**

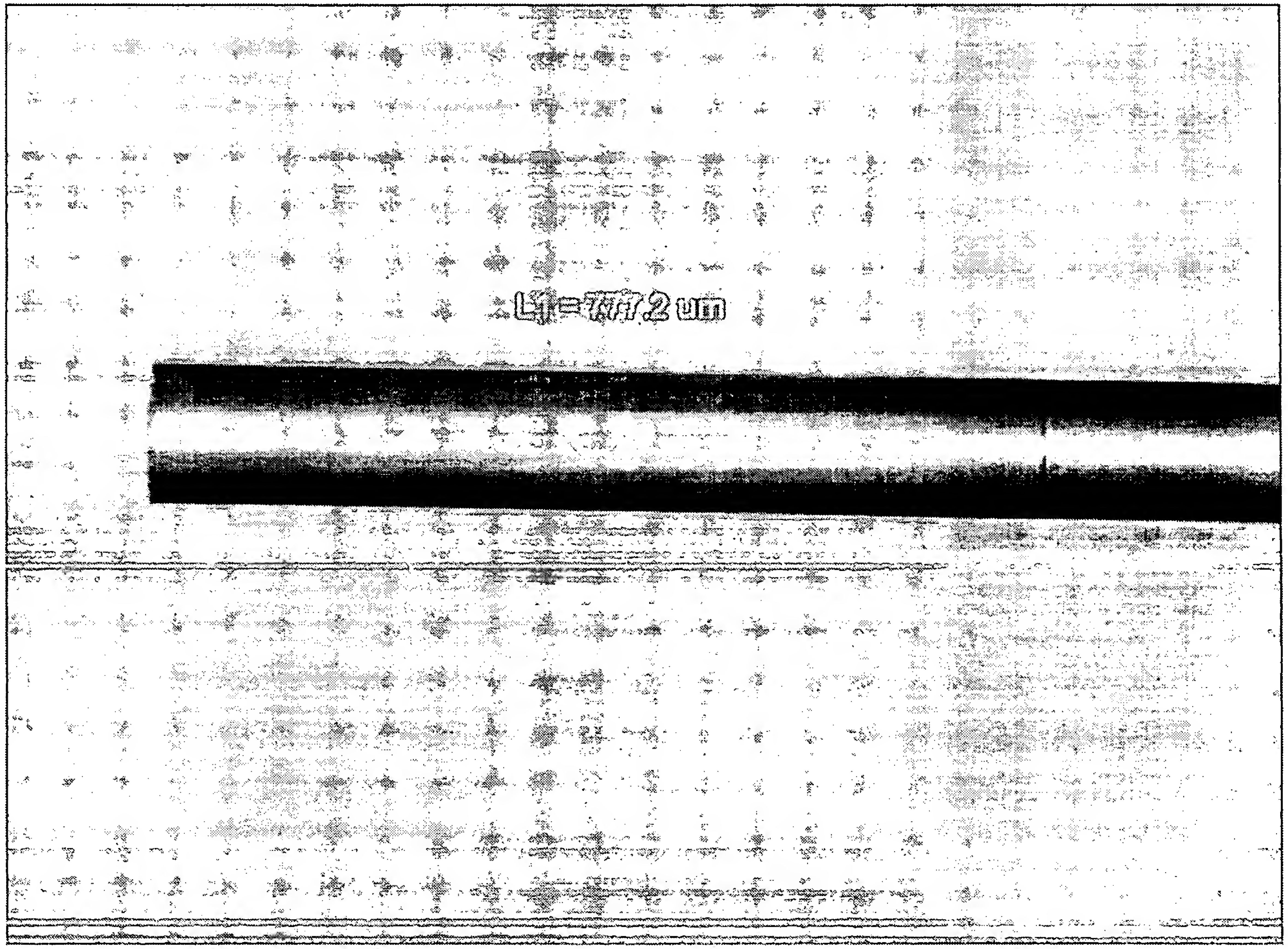
# Loss Budget

**Single mode fiber - custom Grin fiber assembly**

| | | stdev of insertion loss |
|---|---|---|
| **Fiber misalignment** | | |
| - axial misalignment: ±10 μm | ⇒ | 0.007 dB |
| - lateral misalignment: ±1.4 μm | ⇒ | 0.041 dB |
| - rotational misalignment: ±2° | ⇒ | 0.013 dB |
| **MEMS mirror losses** | | |
| - gold reflectivity: 97.7% | ⇒ | 0.103 dB |
| - mirror roughness (cosine ripple): | ⇒ | < 0.001 dB |
| - mirror verticality: 90° ± 0.5° (± 0.25°) | ⇒ | 0.585 dB (0.148 dB) |
| **Optical system losses** | | |
| - Fresnel reflections: 1% AR-coating | ⇒ | 0.087 dB |
| - grin section length: ±20 μm | ⇒ | 0.107 dB |
| - angle cleaved facet: ±0.3° | ⇒ | 0.065 dB |
| - SMF-Grin fiber core alignment: ±1 μm(±0.5 μm) | ⇒ | 0.227 dB (0.056 dB) |

$$\text{Total loss} = \sqrt{\sigma^2_{axial} + \sigma^2_{lateral} + \sigma^2_{rotational} + \ldots} + IL_{gold} + IL_{Fresnel} = 0.83\ \text{dB}\ (0.4\ \text{dB})$$

# Optics Sub-Assembly



# Optics Sub-Assembly Work Instructions

## 1. ABOUT THIS DOCUMENT

### 1.1. PURPOSE

This document identifies the equipment, establishes the process and details the validation of optical sub-assemblies for MEMS 1x2 and 2x2 switch construction.

### 1.2. SCOPE

This procedure applies to the construction and validation of 250 μm fiber-based optical subassemblies for use in MEMS switches.

### 1.3. REVISION CONTROL

When any part of this procedure requires amendment, the document shall be re-issued in its entirety. Requests for changes shall be addressed to the MEMS development Design Control Board (DCB).

| REV | DATE | REASON | ORIGINATOR |
|---|---|---|---|
| -- | 05 Oct | Draft | Bob Hallock |
| -- | 03 Nov 00 | Draft | Leland Black |

# Optics Sub-Assembly Work Instructions

1. PROCEDURE

1.1. Perform ‘Arc Check’ with a piece of SMF and CMMF at the beginning of each shift

1.2. Cut 6 inch piece of CMMF

1.3. Strip 2 inches of buffer from CMMF

1.4. Place into fiber holder

1.5. Clean CMMF using ultrasonic cleaner

1.6. Place #1 spacer block to left of fiber clamp, Ericsson cleaver

1.7. Mount fiber holder to left of cleaver (left of spacer block)

1.8. Center fiber in guide on right cleaver clamp

1.9. Secure right cleaver clamp

1.10. <u>Do Not Close</u> left cleaver clamp

1.11. Apply tension (lever)

1.12. Cleave fiber

# Optics Sub-Assembly Flowchart

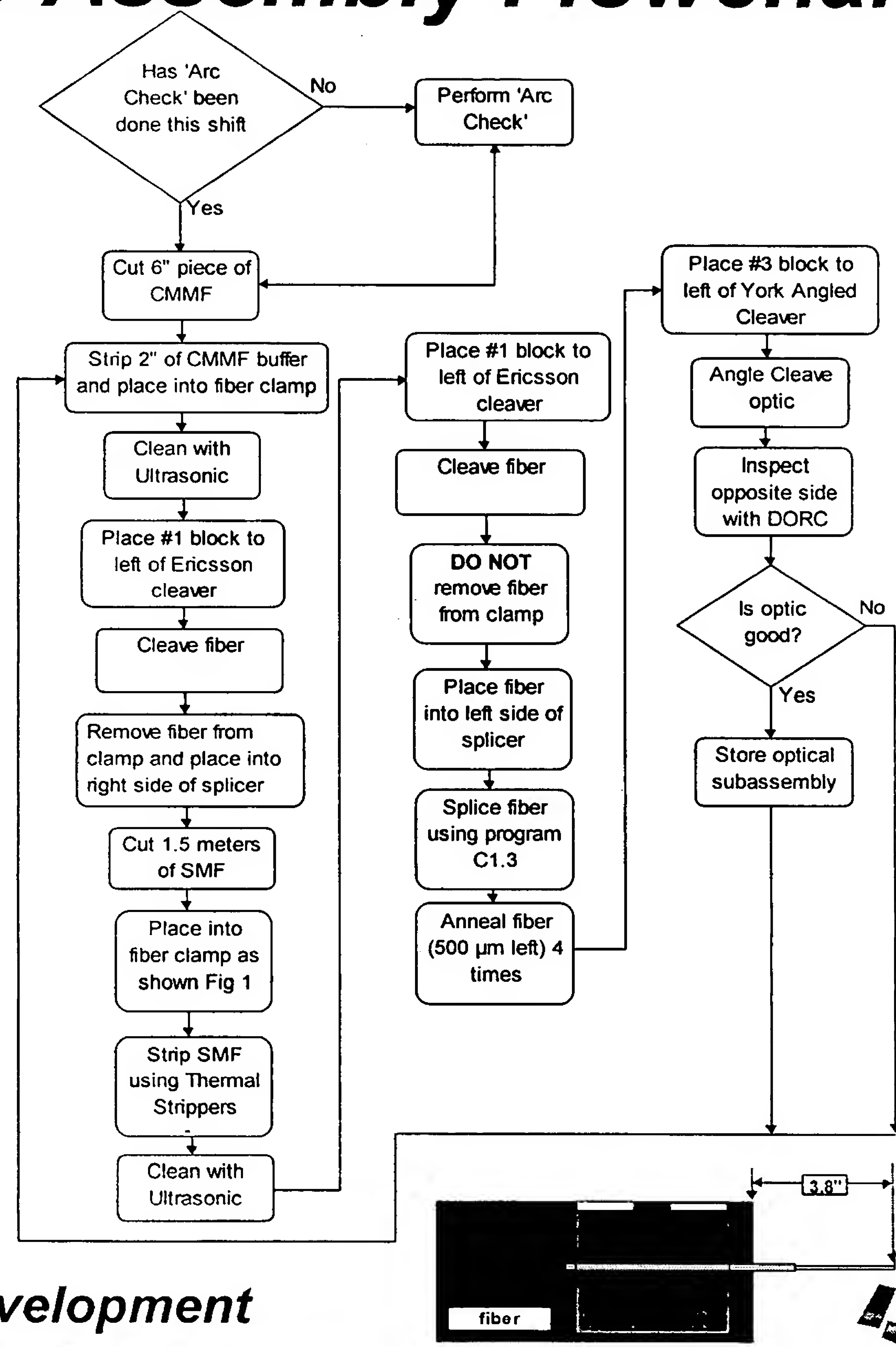



Fig-1

MEMS Product Development

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# Optics Sub-Assembly Layout

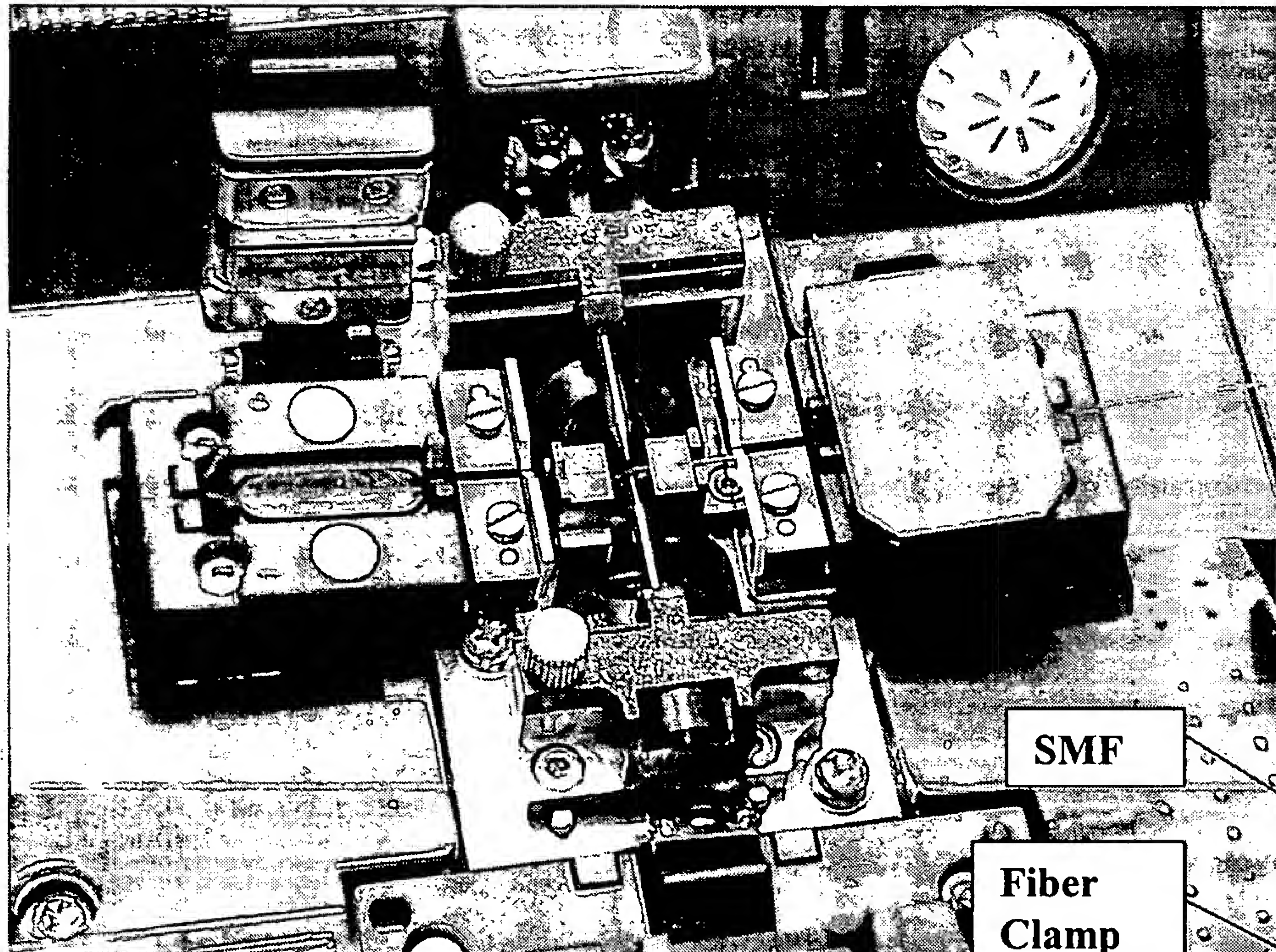
- Mount fiber in small bobbin; leave two pigtails exposed
- End customer removes the bobbin
- Strip single mode fiber using thermal mechanical strippers
- Cleave fiber precise distance from end of strip. Use ground 416 SS block to locate this cleave.
- Fuse to custom multi mode grin fiber using cladding fiber alignment.
- Index (?) and angle cleave multi mode. Use a second larger 416 SS block to achieve grin length.

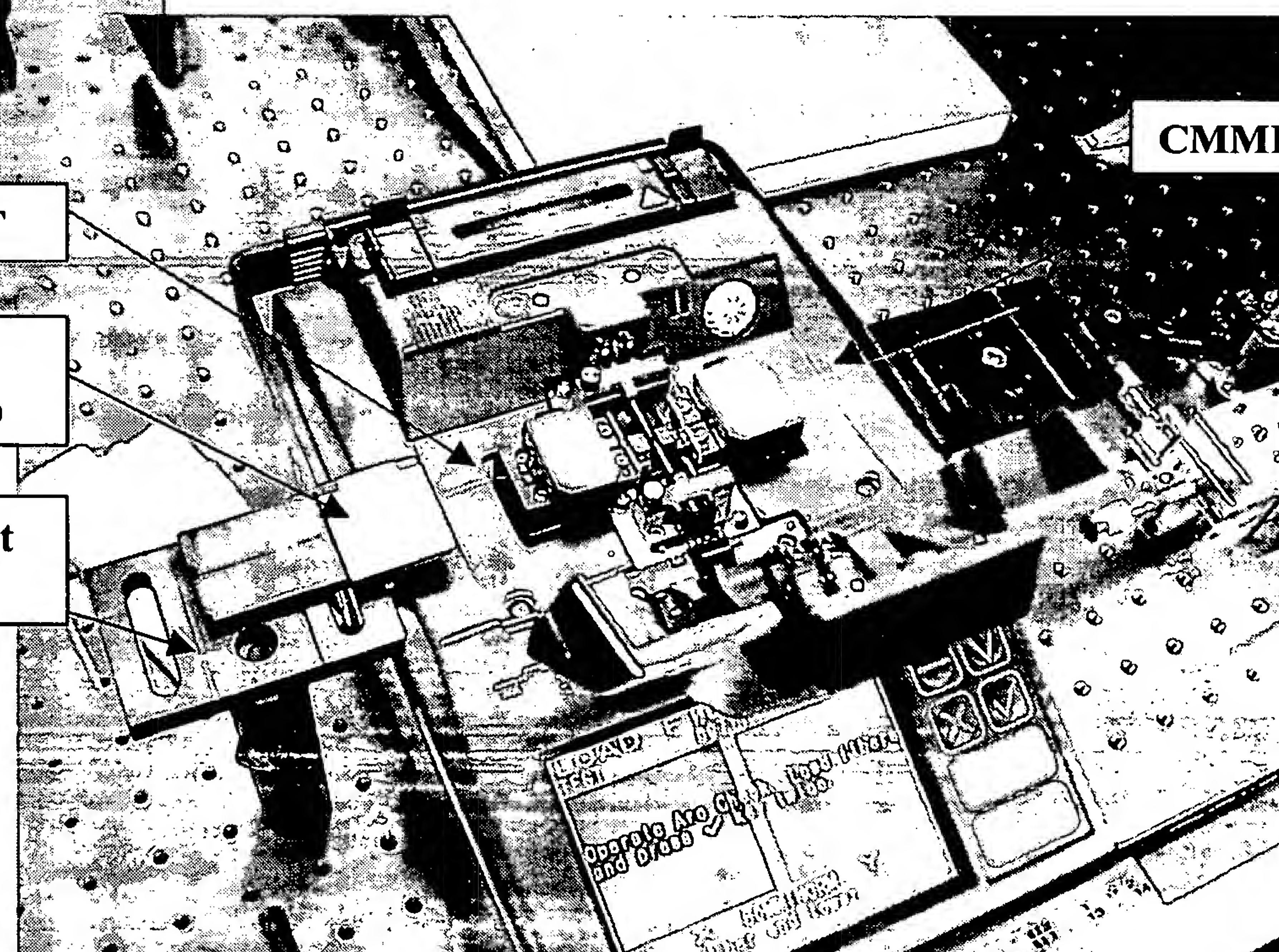
# *Optics Sub-Assembly Con't*

- Test optics with a GO / NO GO test station
- If optics are unacceptable, rework.
- Load fiber into AR coating tooling.
- Coat fibers
- Retest optics
- Store in dry box until assembly into chip.

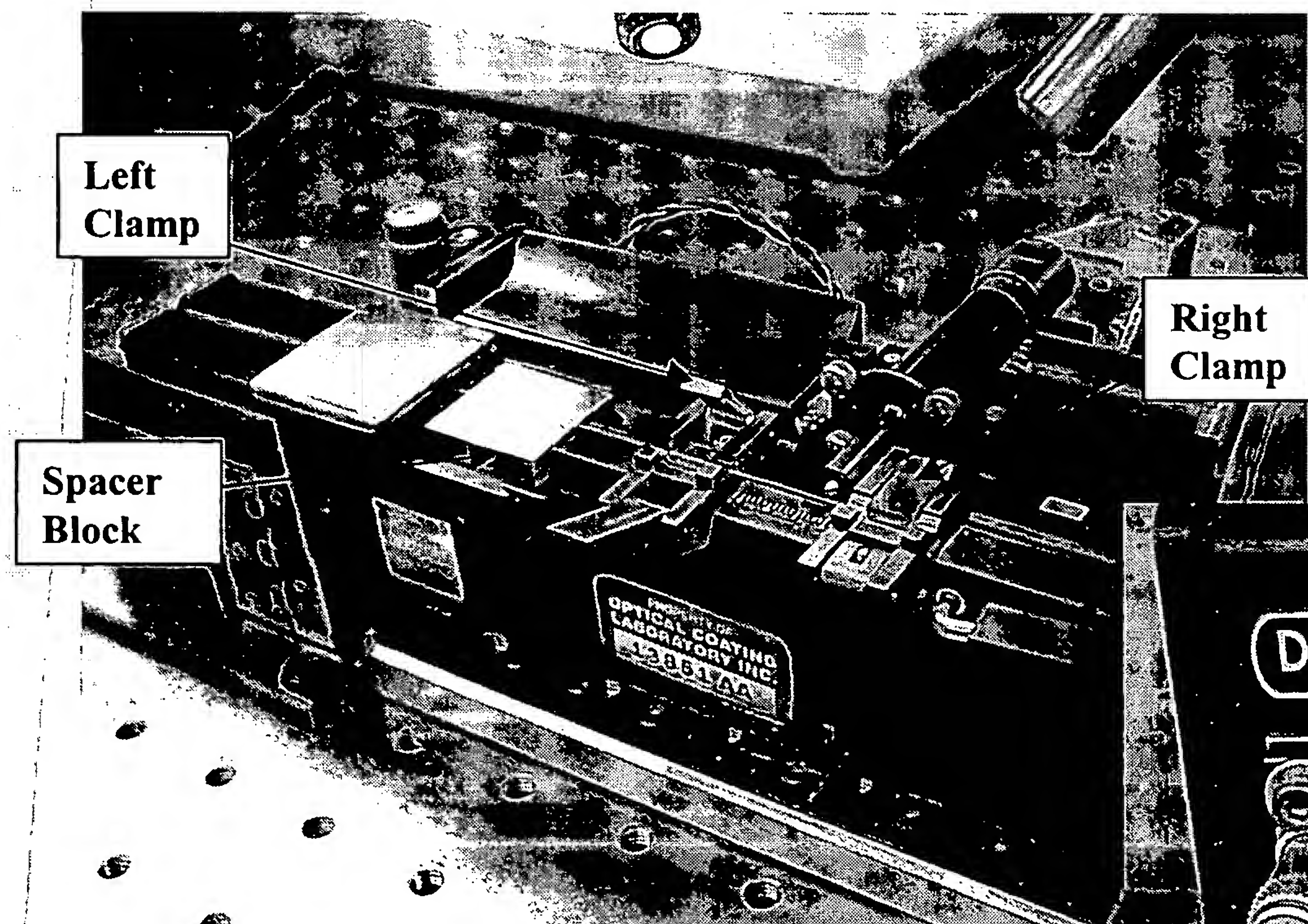
# Fusion Splice Multimode 'Grin' Optic to SMF28 Fiber

- Cladding alignment between SM and MM fiber.
- Fiber clamp is along for the ride during splice step.





# Optical Assembly Tooling - Fiber Cleave



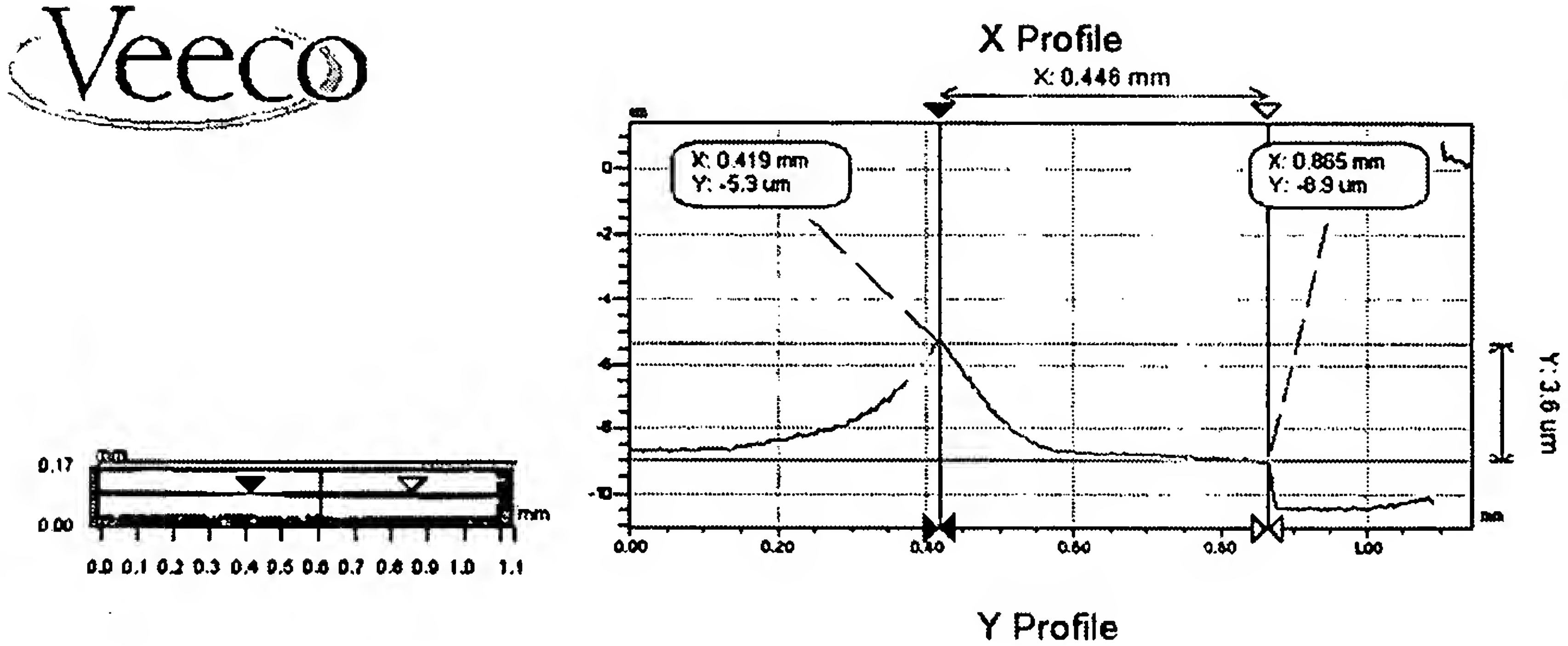

- Stainless steel spacer block and tension cleaver


- Interferometer instrument to inspect cleaved surface

# *Optical Sub-Assembly Cycle Times*

- 3 minutes per optics including optical inspection.
  - – Does not include yield. Currently ~80% for fiber cleave, fiber anneal and length.
- Need to develop optical GO/NO GO test for insertion loss. Currently just optical inspection with DORC.
  - – Any yield loss others then those listed above should be systematic errors, not random.
    - Example: core concentricity, ‘GRIN’ profile change.

# Splice bump

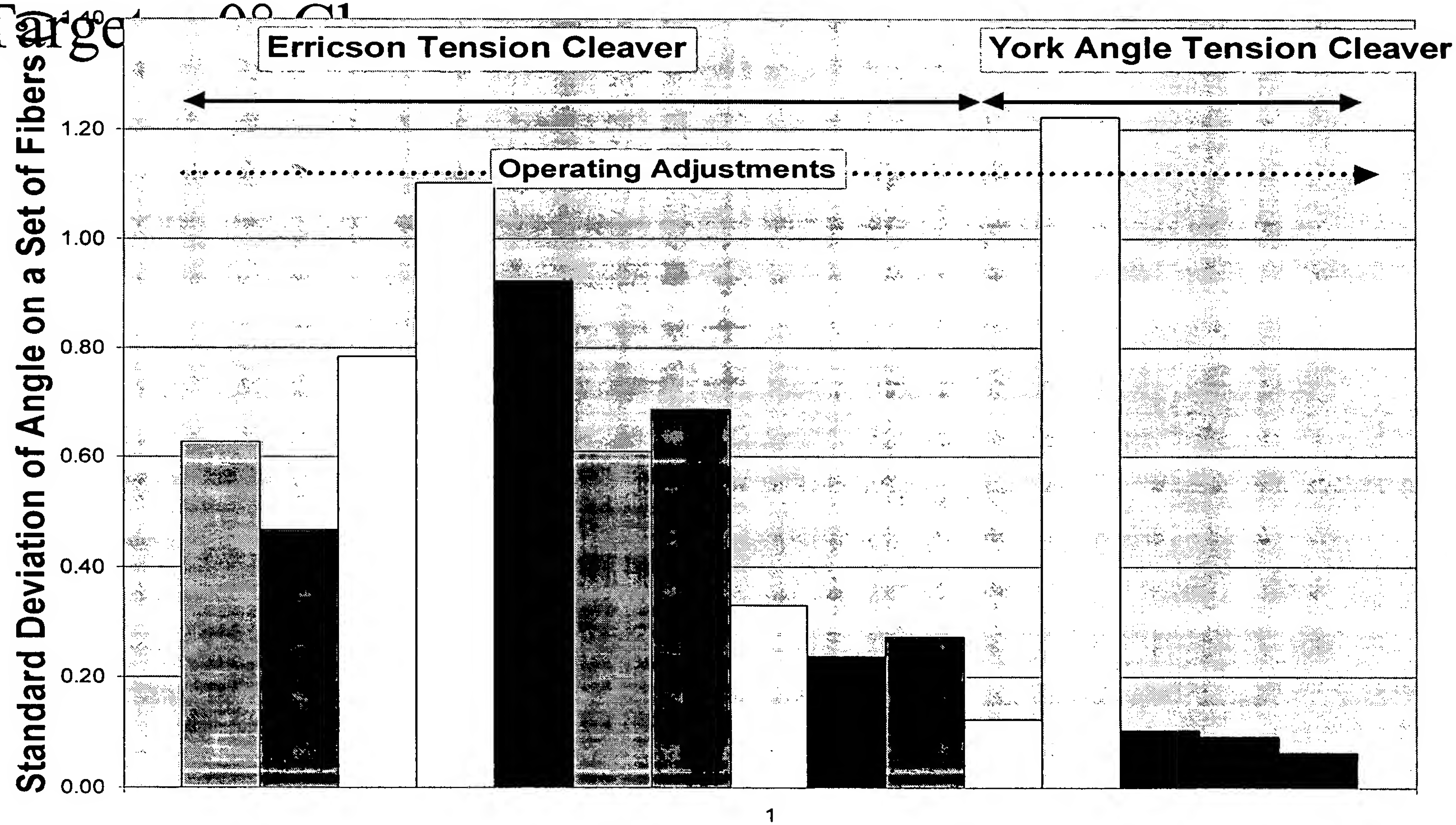



- HighWave Gradissimo purchased fibers. Would not fit into fiber trenches due to bump at splice location.

- Initial internally manufactured optics exhibited similar problem.
- Current solution: during fusion arc 'pull' on fibers to reduce bump.
- Future addition: add relief area to sides and bottom of fiber trench to assure there is no contact with splice joint.

# Cleaver Comparison

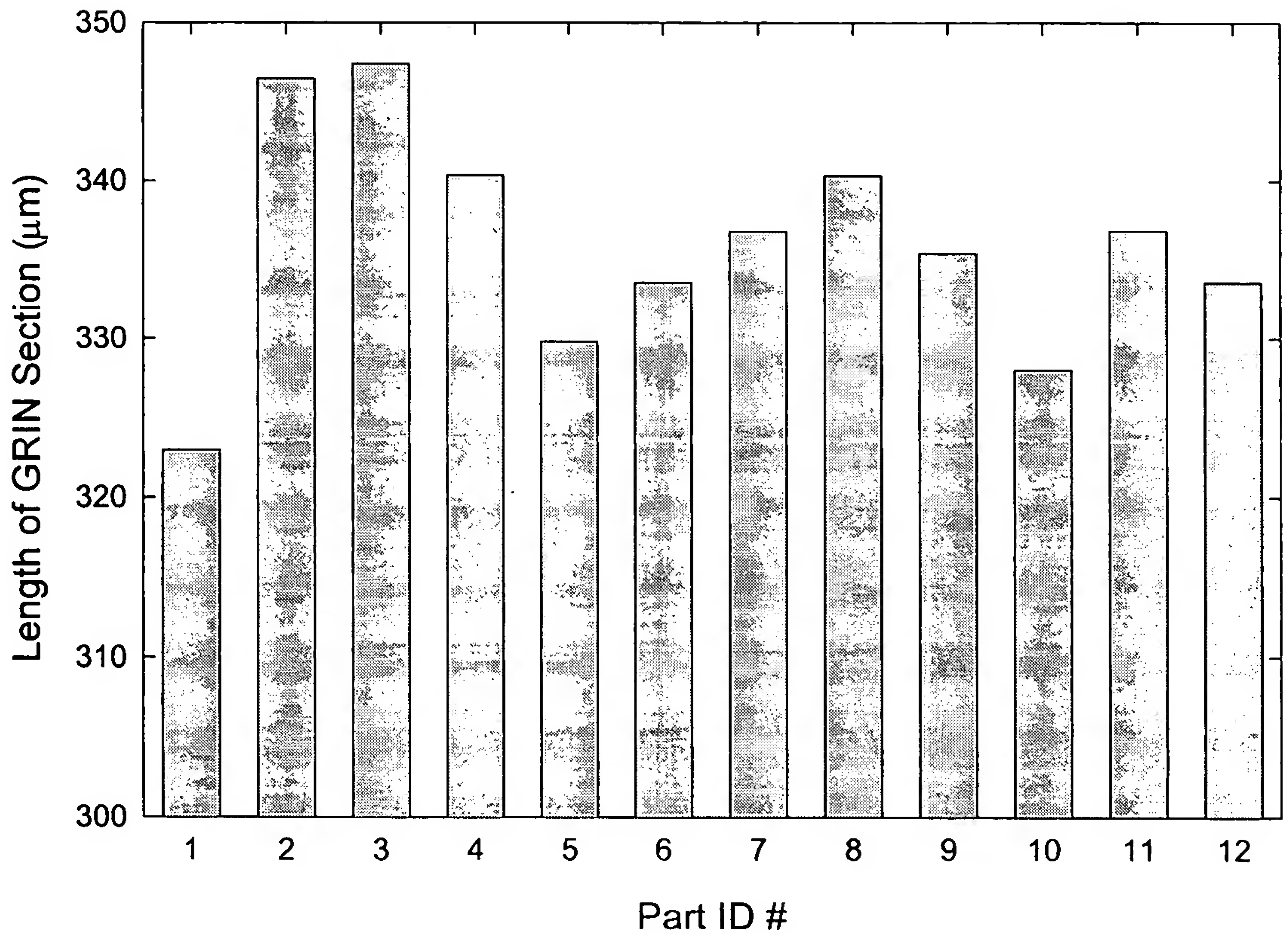
Targe



# Standard 'Off the Shelf' 50μm Multimode GRIN Fiber

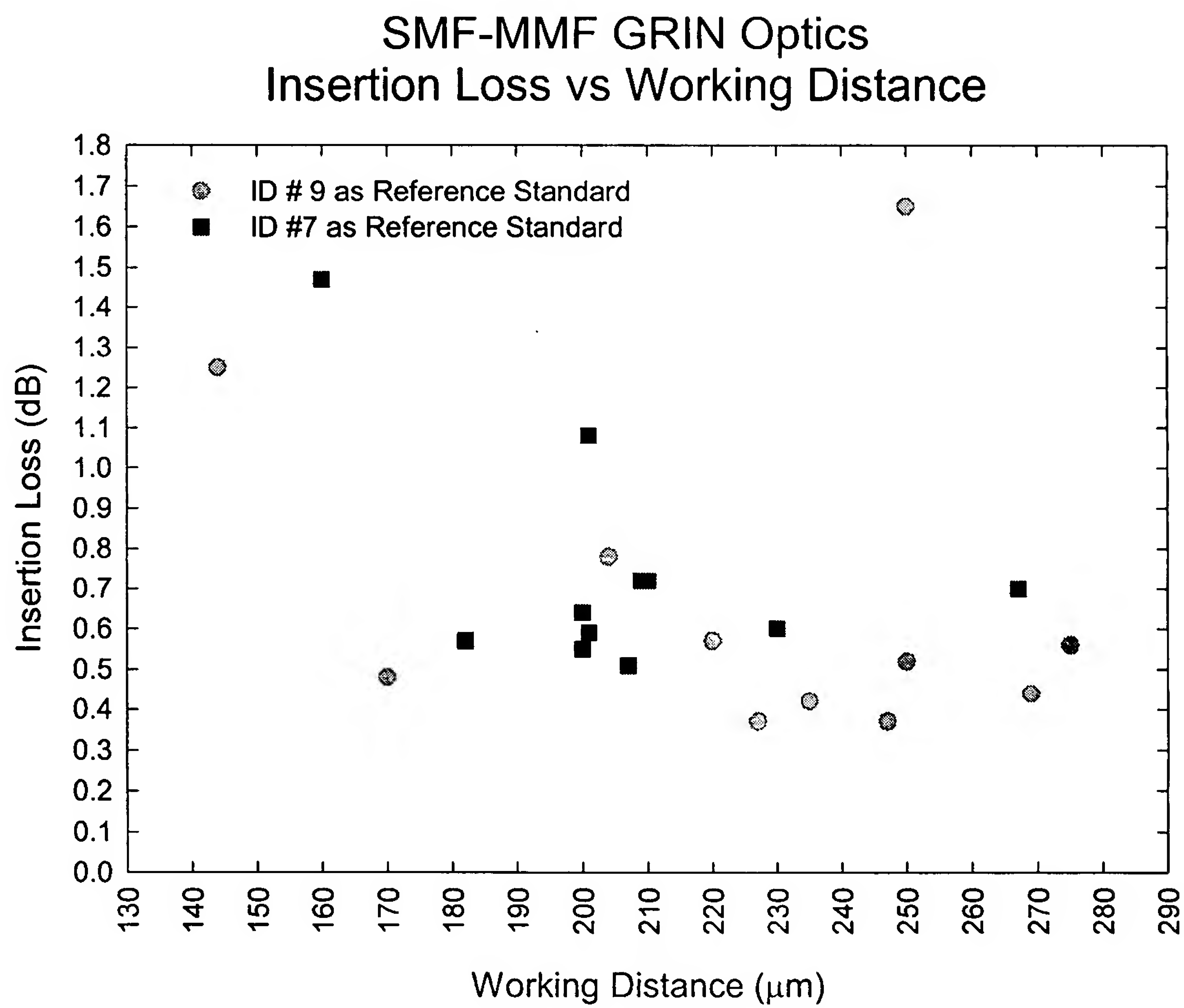
# Standard MM 'Grin' Fiber Cleave Length

SMF-MMF GRIN Length



# Insertion Loss - Free Space Transmission - Standard MM Fiber

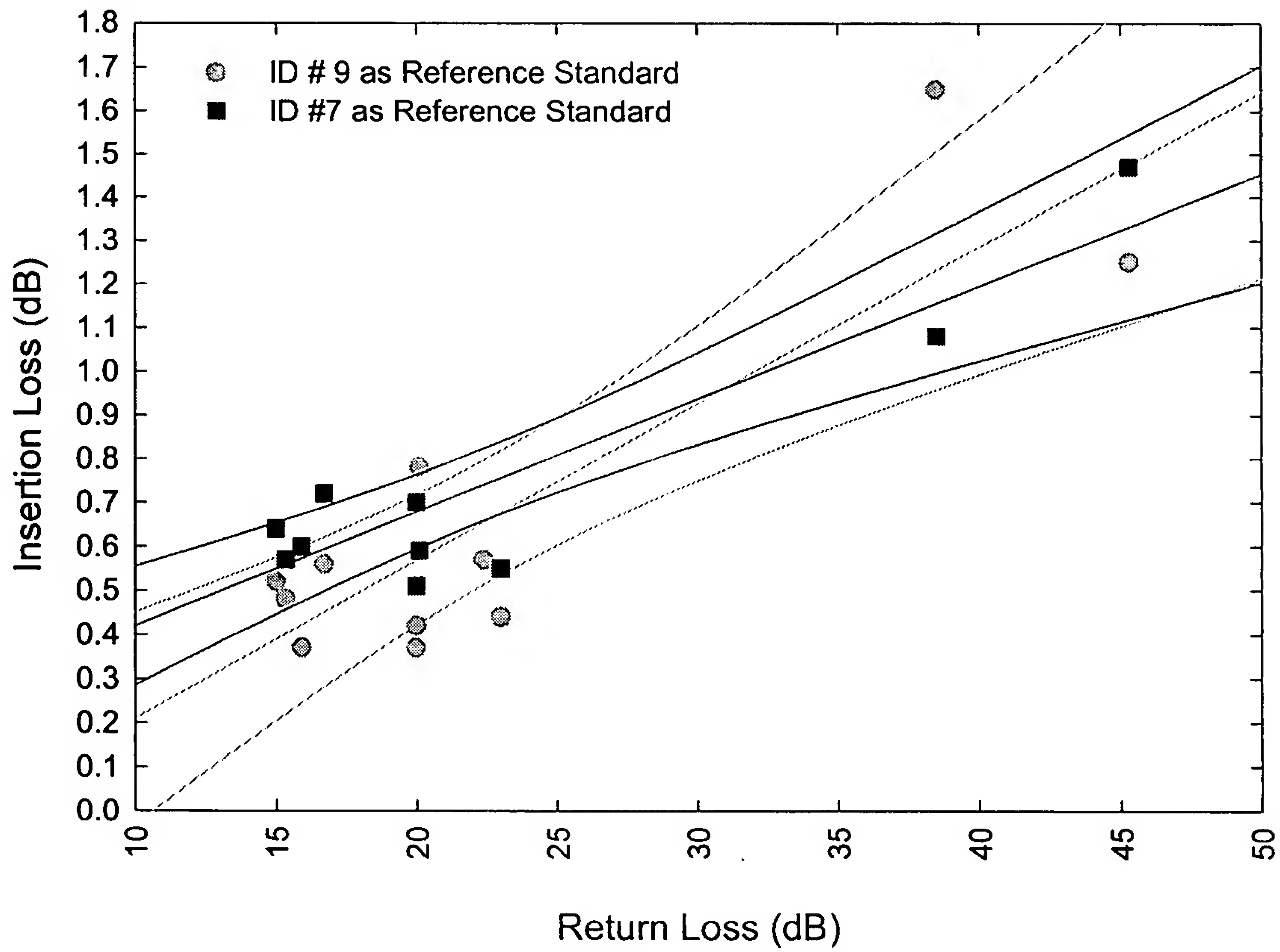
- No AR coating on these optics



# Standard MM Fiber Return Loss

- No AR coating on these optics

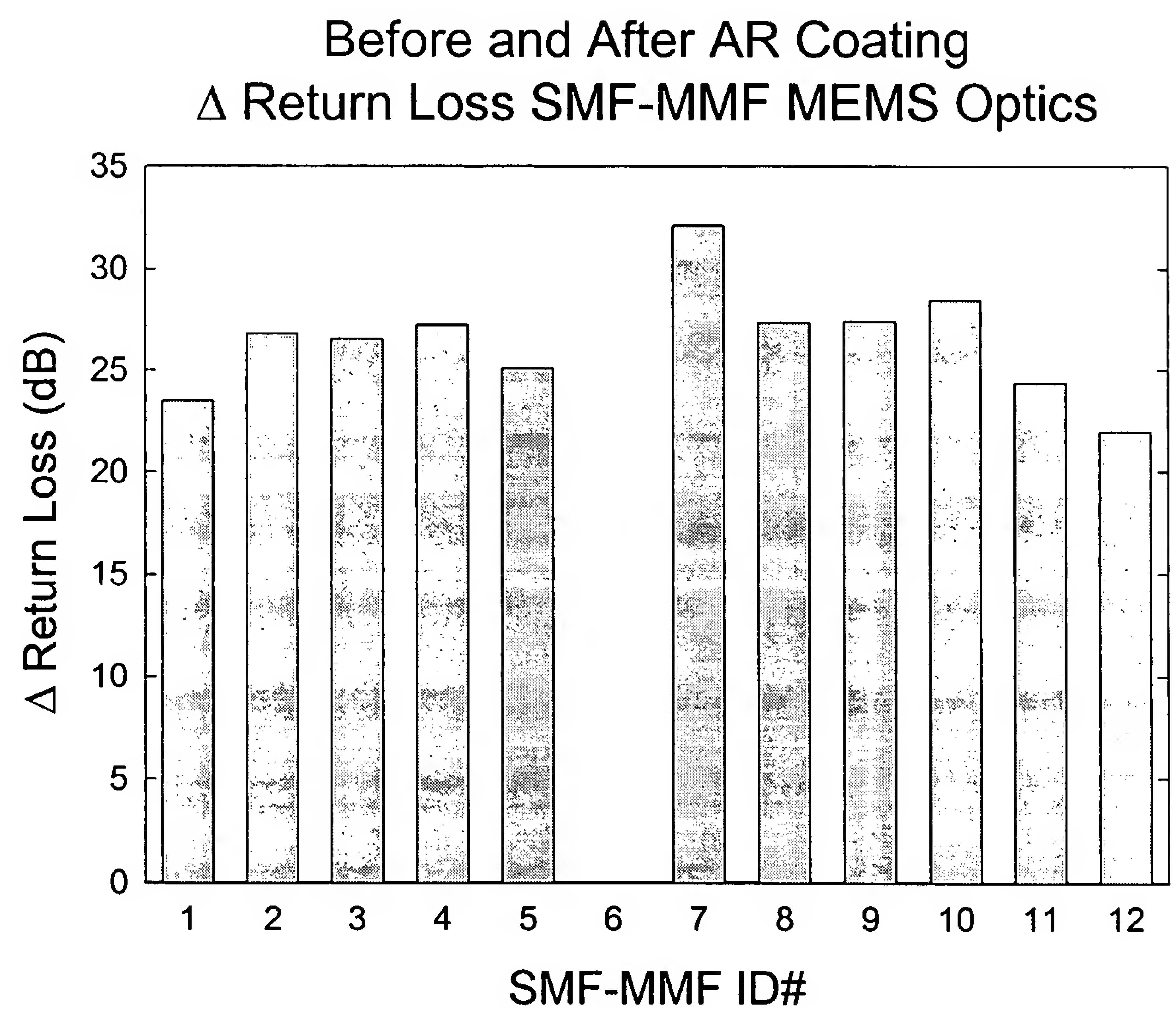
SMF-MMF GRIN Optics
Insertion Loss vs Return Loss



# AR Coating

- Initial tooling near complete.
- Cycle time 1.5 to 2 hours, coating chamber only (no loading).
- 78 optical assemblies per set of tooling.
- 4 or 6 tooling units capable per coating run.
- 10 sec per part optical assembly loading time estimation. ~ 1 hour to load complete coating chamber.

# Return Loss After AR Coating



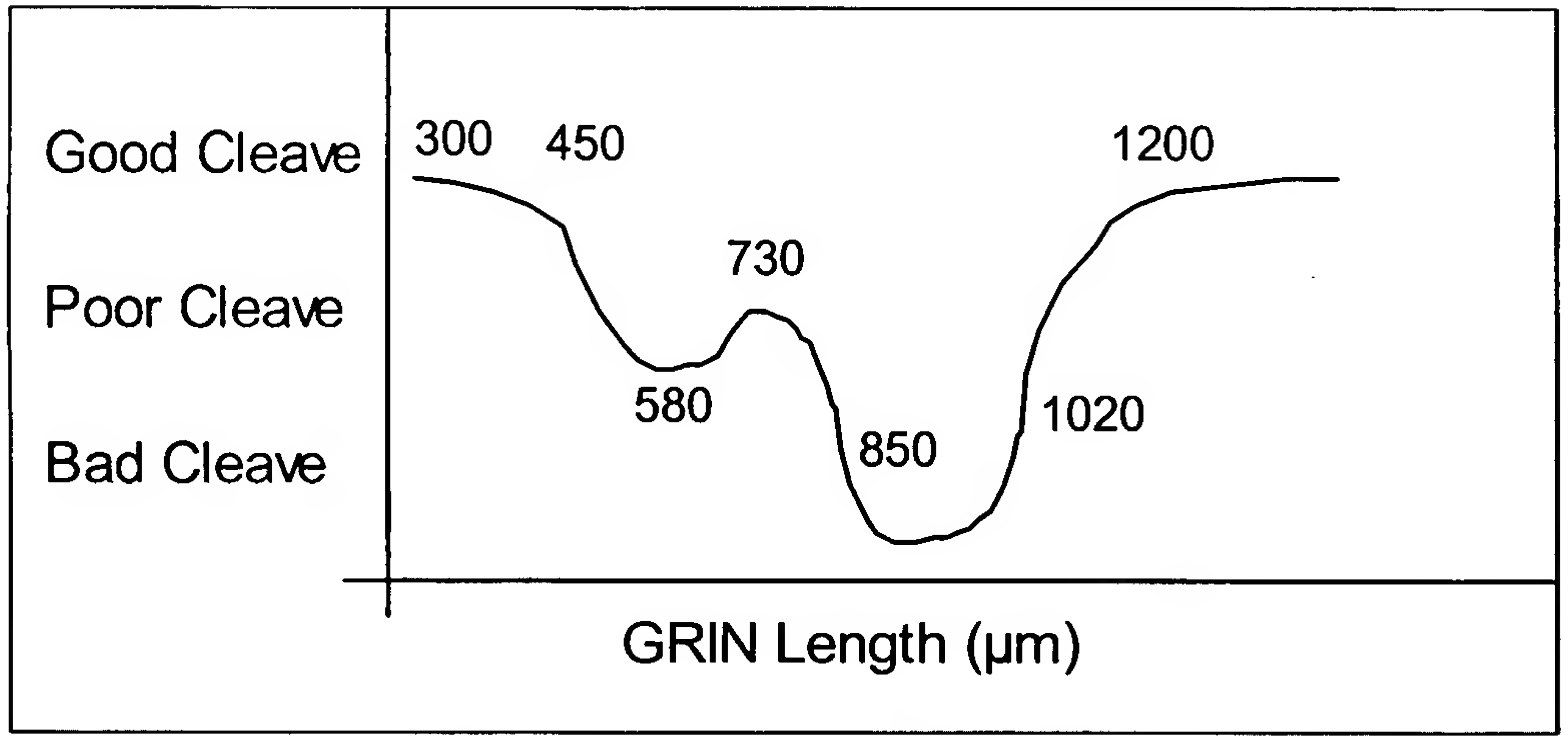
# Temperature Dependant Insertion Loss - Standard MM Fiber

| Chip ID | Delta Insertion Loss Between -5°C and 70°C (dB) | | |
|---|---|---|---|
| 020-E1 | | -0.10 | |
| 025-E1 | | -0.28 | |
| J10-E1 | | -1.68 | |
| K20-E1 | | -0.06 | |
| P15-F1 | | -0.03 | |
| K15-F1 | | -0.03 | |
| J15-F1 | | -0.23 | |
| P20-F1 | | -0.06 | |
| E10-E1 | | -0.03 | |
| SW1 | | -0.06 | |
| Average | -0.26 | dB / °C | 0.003 |
| Average w/o J10-E1 | -0.10 | dB / °C | 0.001 |

- Initial testing indicates a temperature stable design.
- Additional work to be performed to understand outlaying points

# Custom 80µm Multimode GRIN Fiber

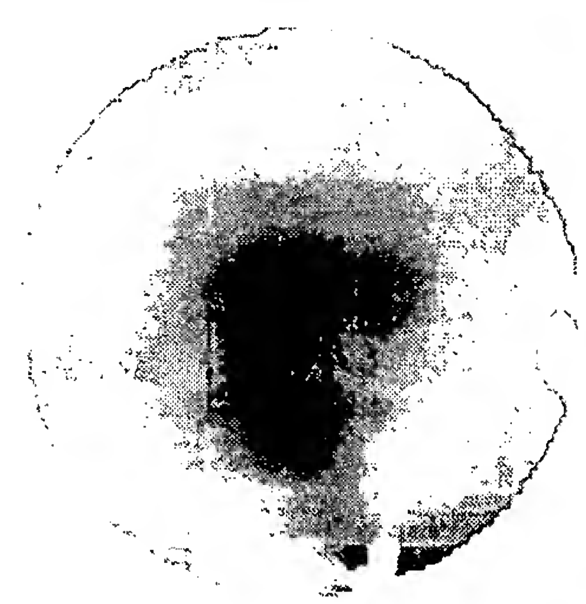
# Straight Cleaving Difficulties - CMMF

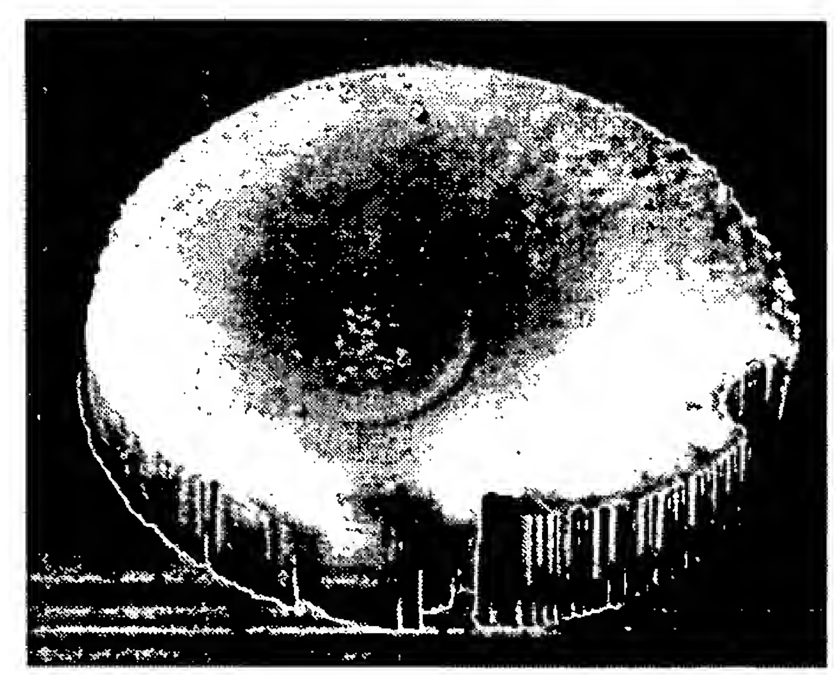



- Qualitative picture of difficulty with cleave. Required ‘GRIN’ length = ~800µm.

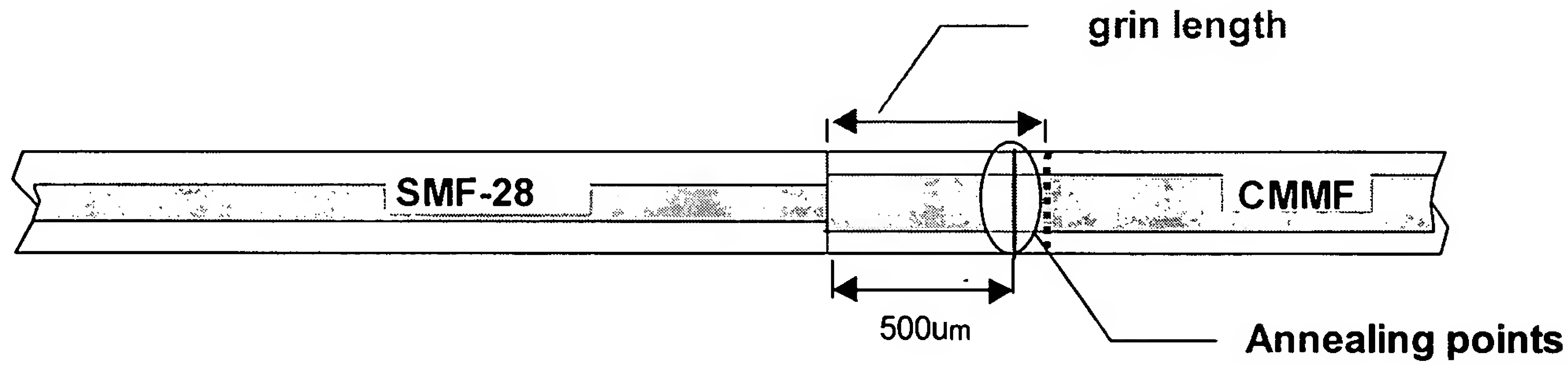
- Example of Good Cleave:

- Example of Bad Cleave:



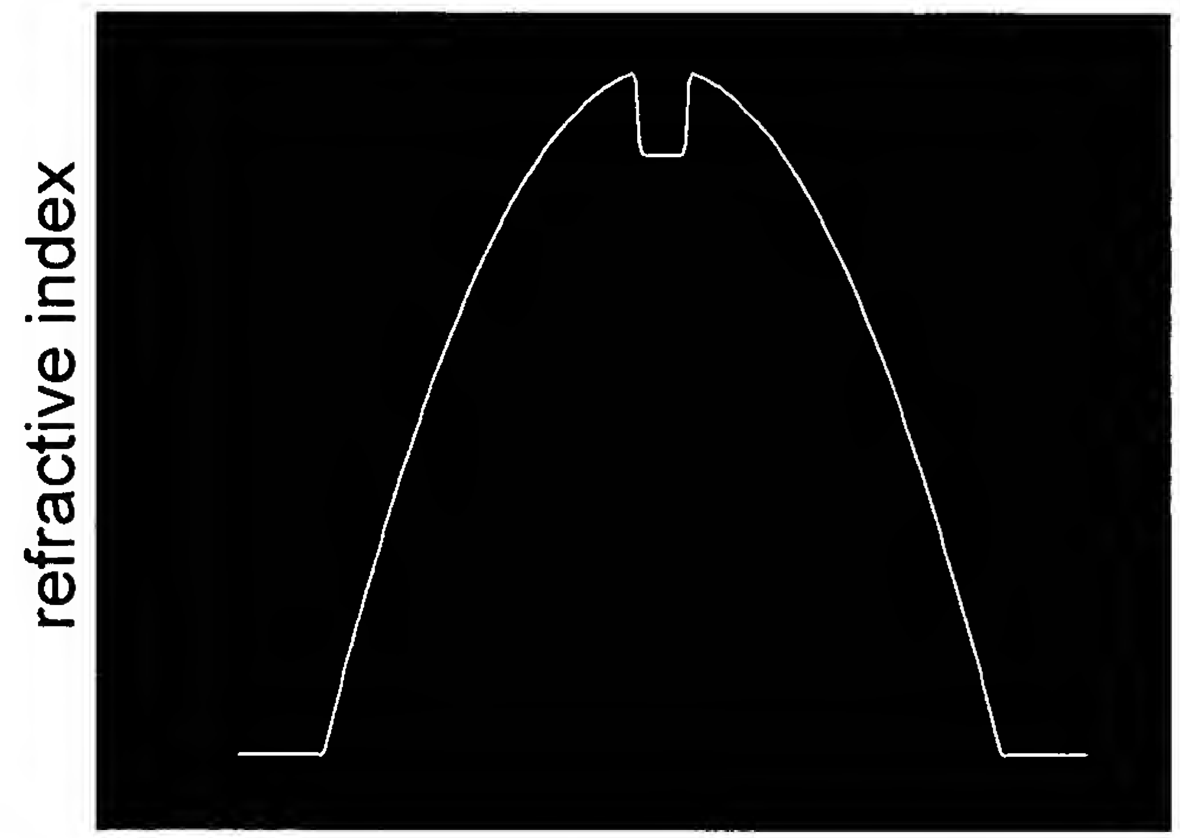


# Annealed CMMF Optics

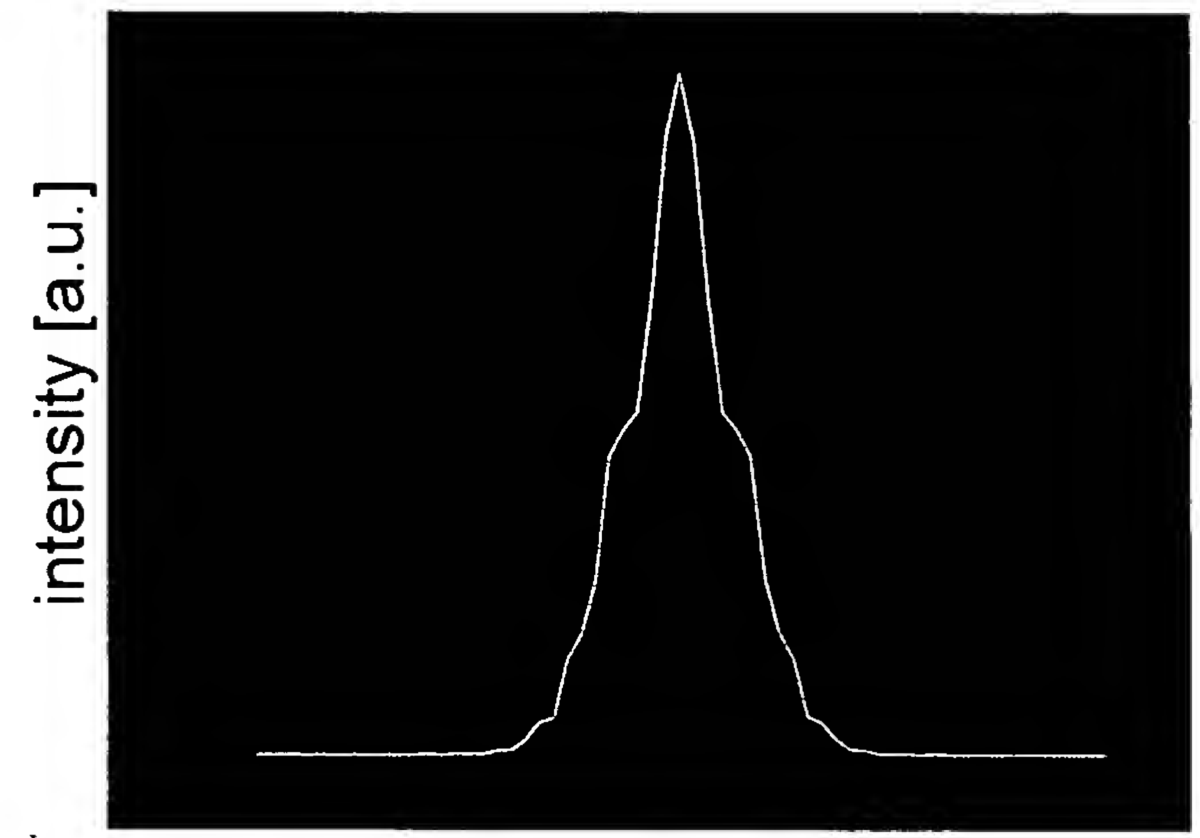



- **In order to achieve flat, smooth cleave surfaces, we had to anneal the CMMF in the area of the 'GRIN' cleave.**
- **Fusion splicer program setup for 4 'cleaning arcs' to be used as the anneal energy.**
- **500 μm is the maximum single input movement for the fusion splicer.**
  - To anneal closer to cleave length would require additional operator inputs.

# Modeling of CMMF with center dip




Refractive index profile



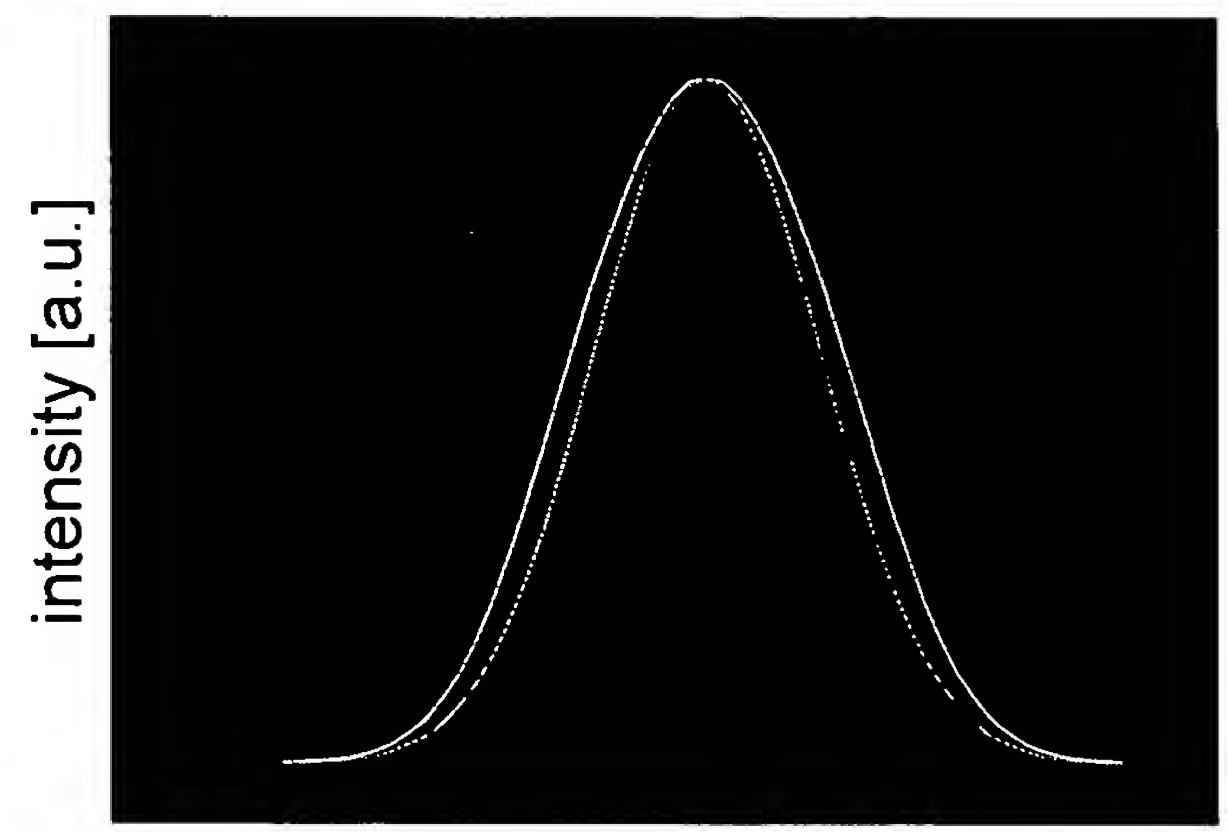

Far-field intensity distribution

refractive index dip: 6 μm diameter
$\Delta n = -0.0011$

best working distance: ideal WD + 60 μm

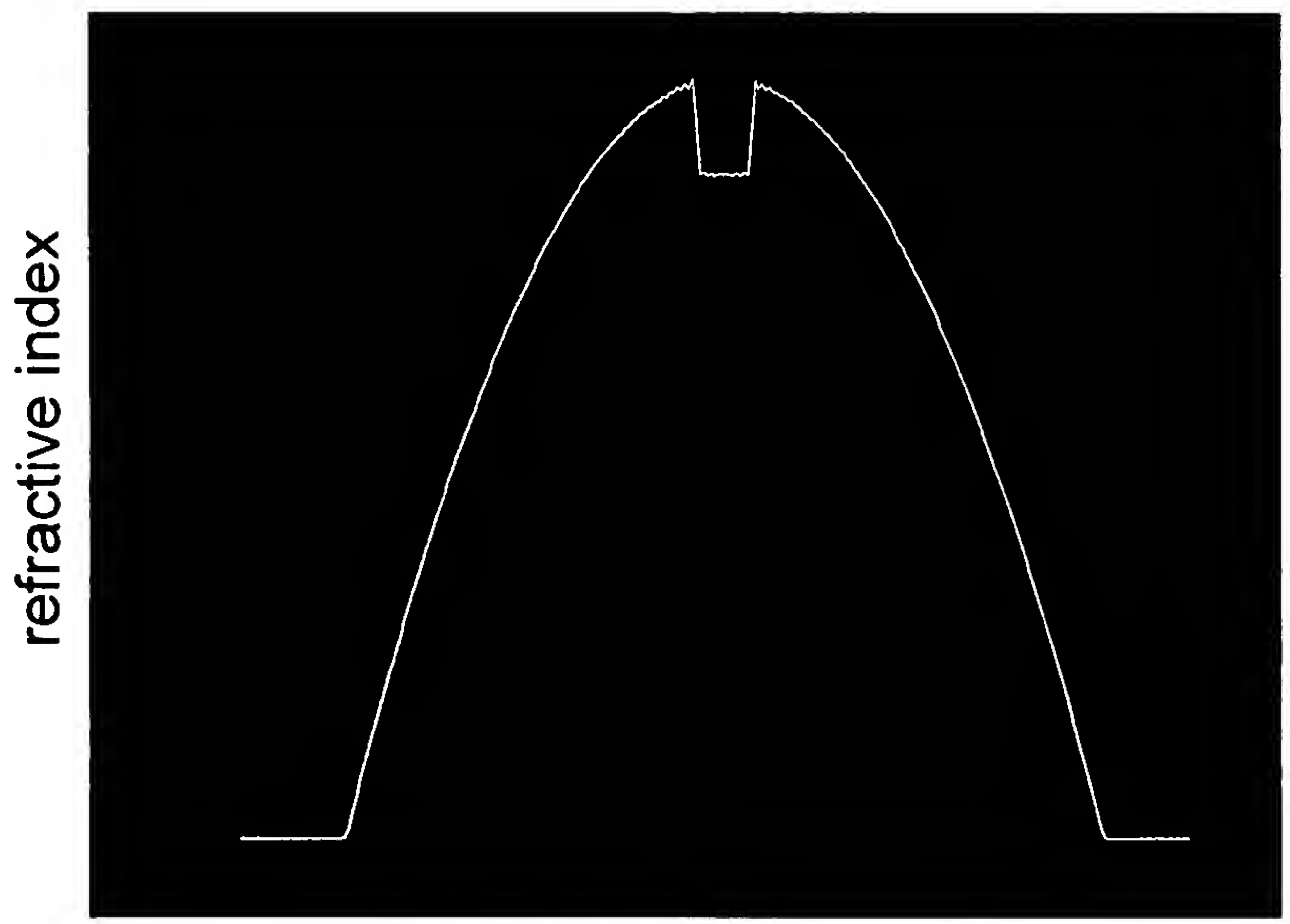
insertion loss:
- ideal infinite Grin profile: -0 dB
- with 80um core diameter: -0.038 dB
- with center dip: -0.226 dB

⇒ additional insertion loss: 0.188 dB

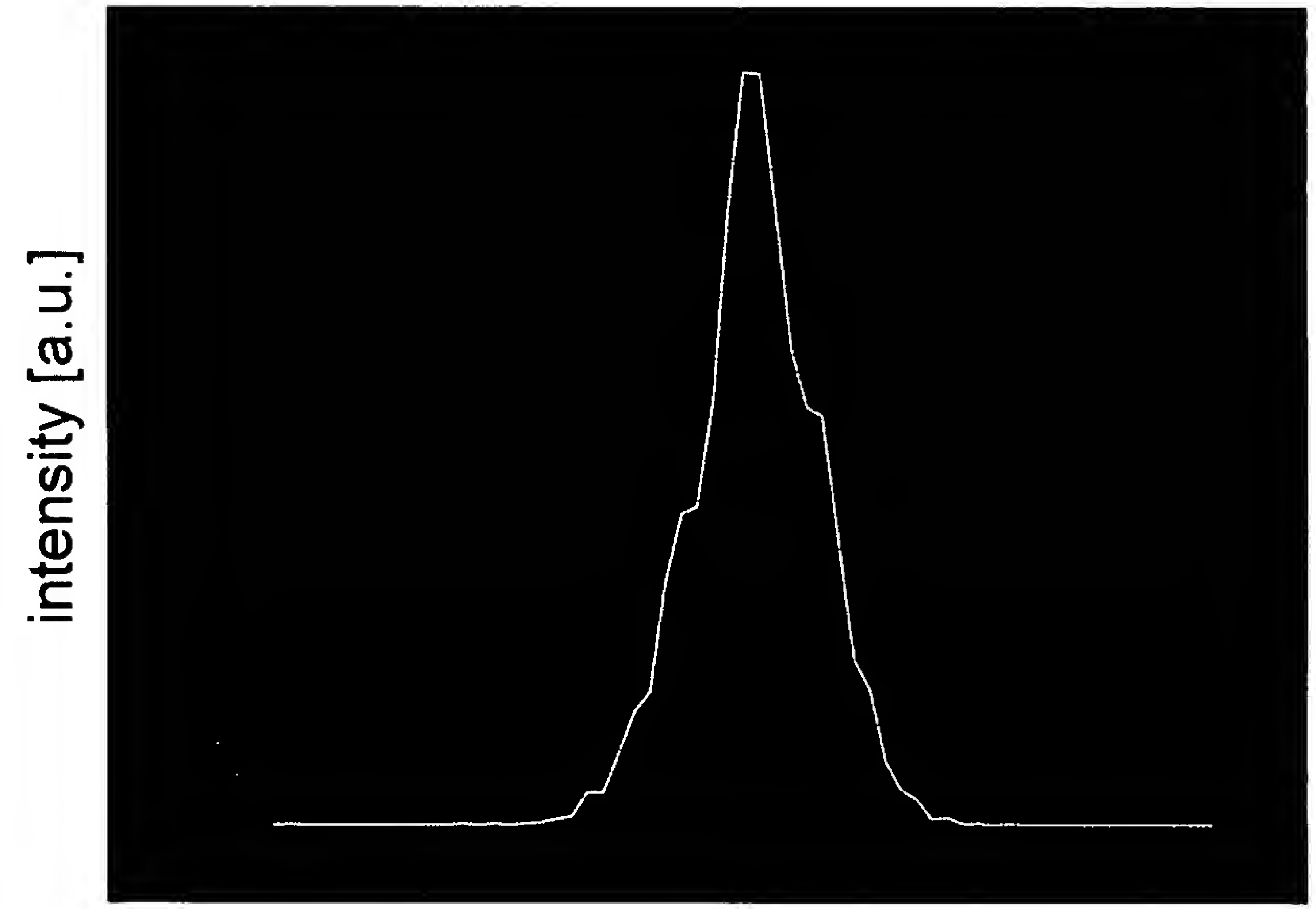



Mode profile at receiving SMF
— ideal — with index dip

# Modeling of CMMF with center dip




Refractive index profile

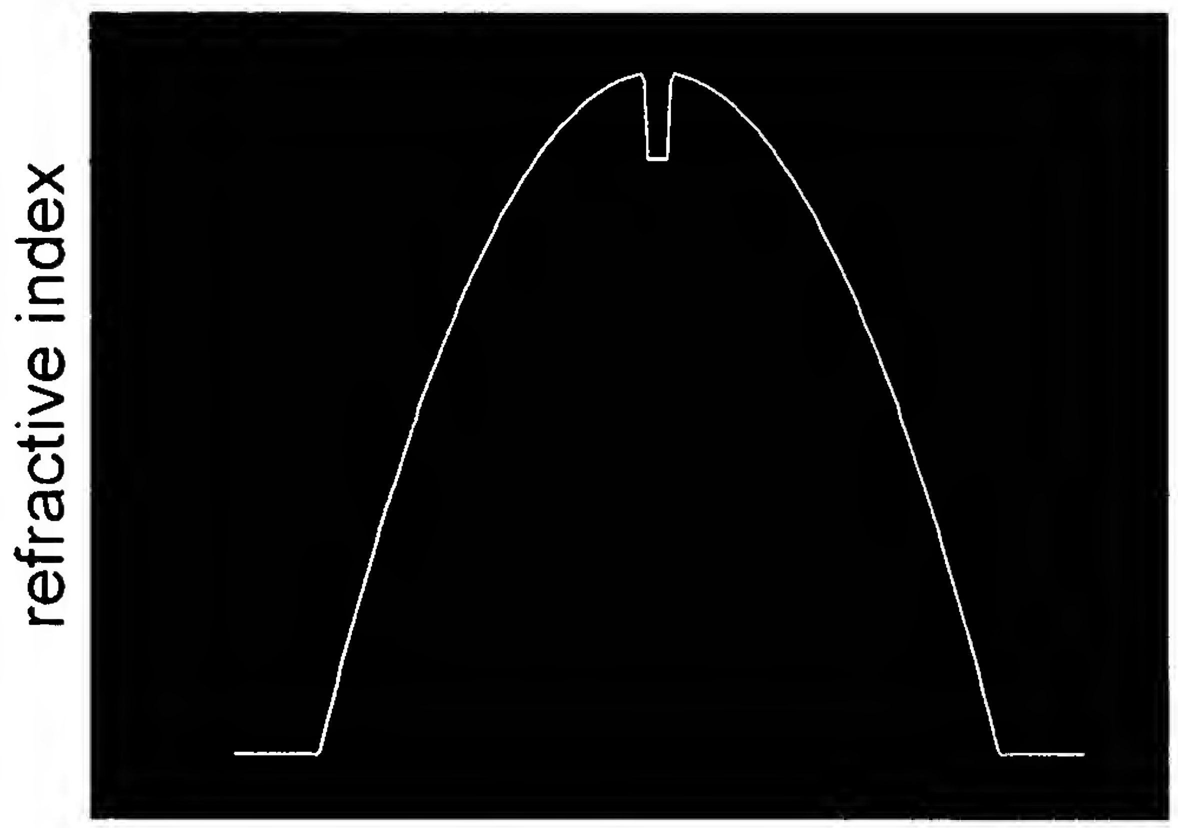



Far-field intensity distribution

refractive index dip: 6 µm diameter
$\Delta n = -0.0011$

refractive index profile shifted by 1 µm off center

# *Modeling of CMMF with center dip*

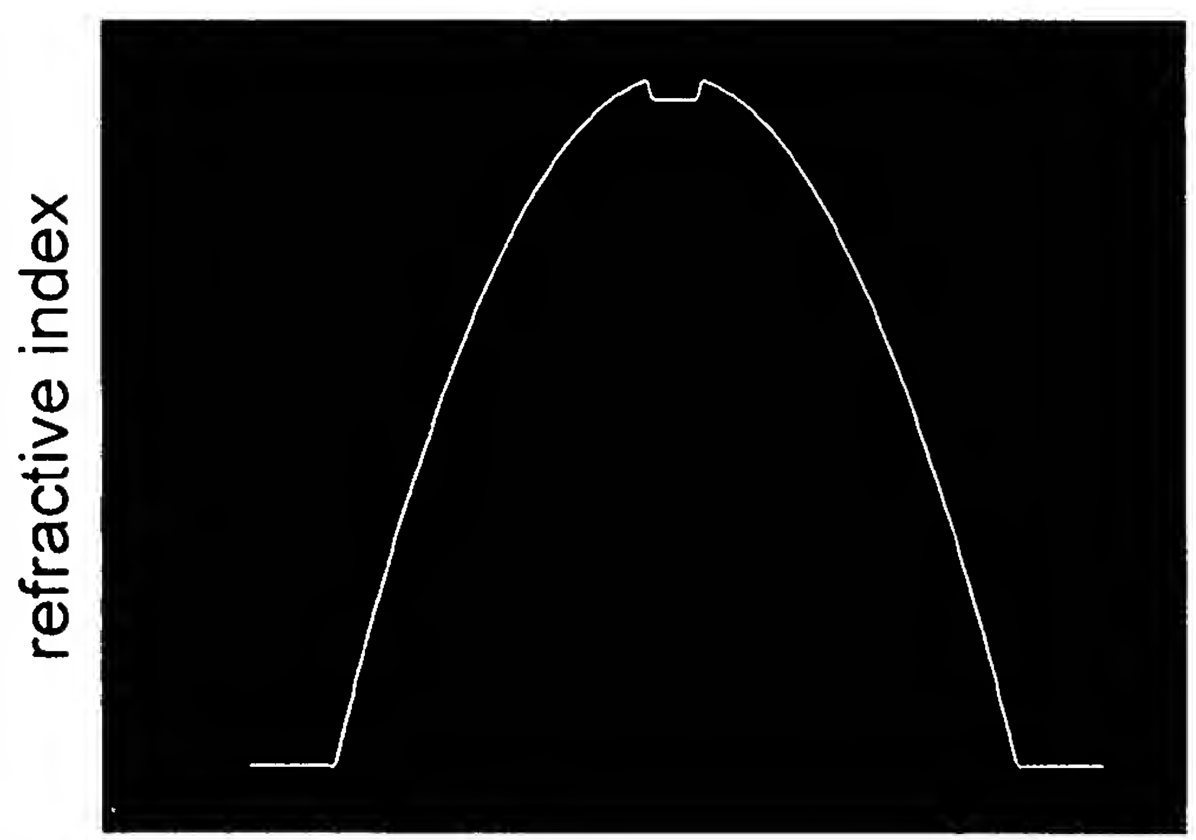


Refractive index profile

refractive index dip: **<u>3 μm diameter</u>**
$\Delta n = -0.0011$

best working distance: ideal WD + 16 μm

$\Rightarrow$ additional insertion loss: < 0.045 dB



Refractive index profile

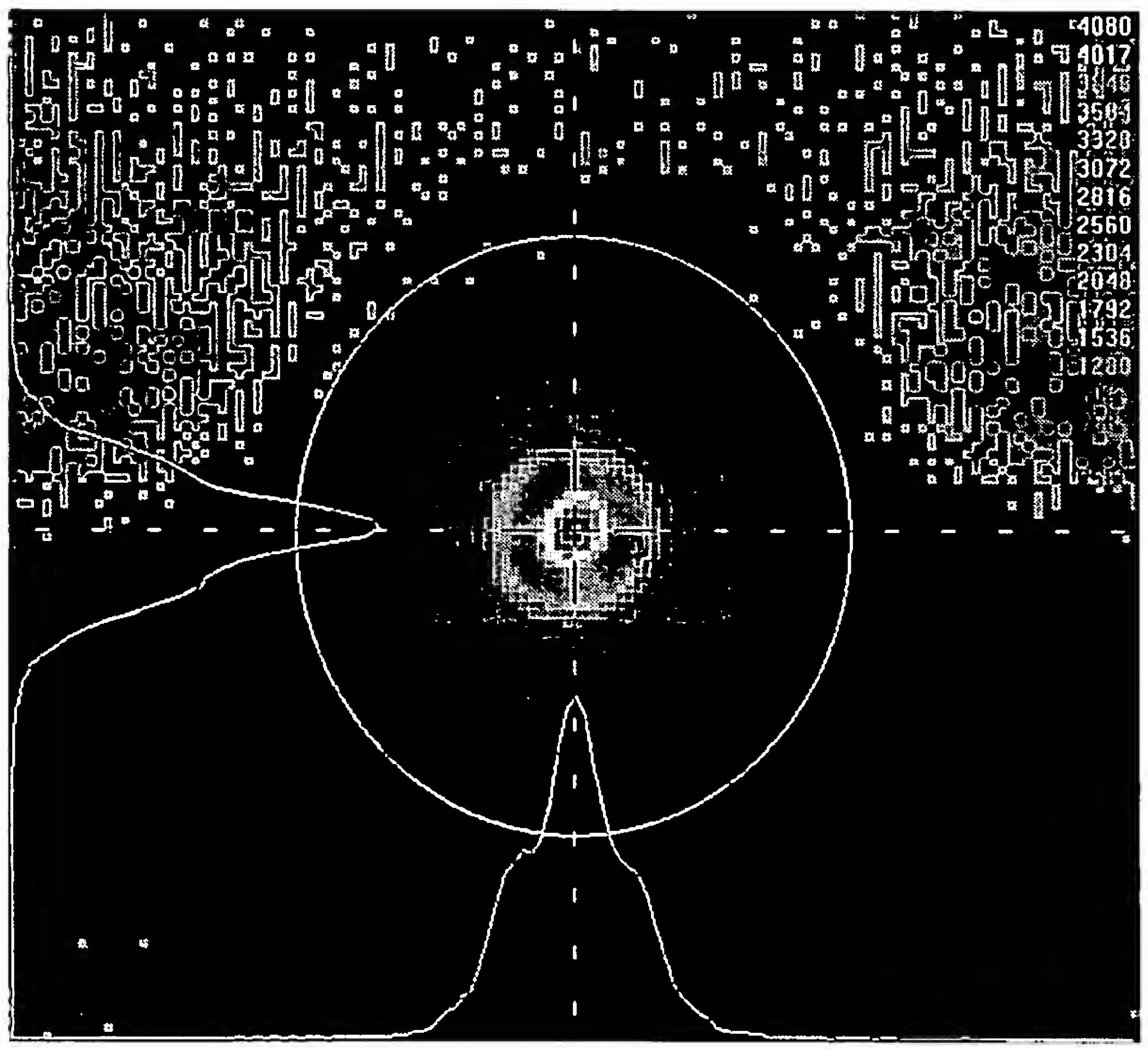
refractive index dip: 6 μm diameter
**<u>$\Delta n = -0.0004$</u>**

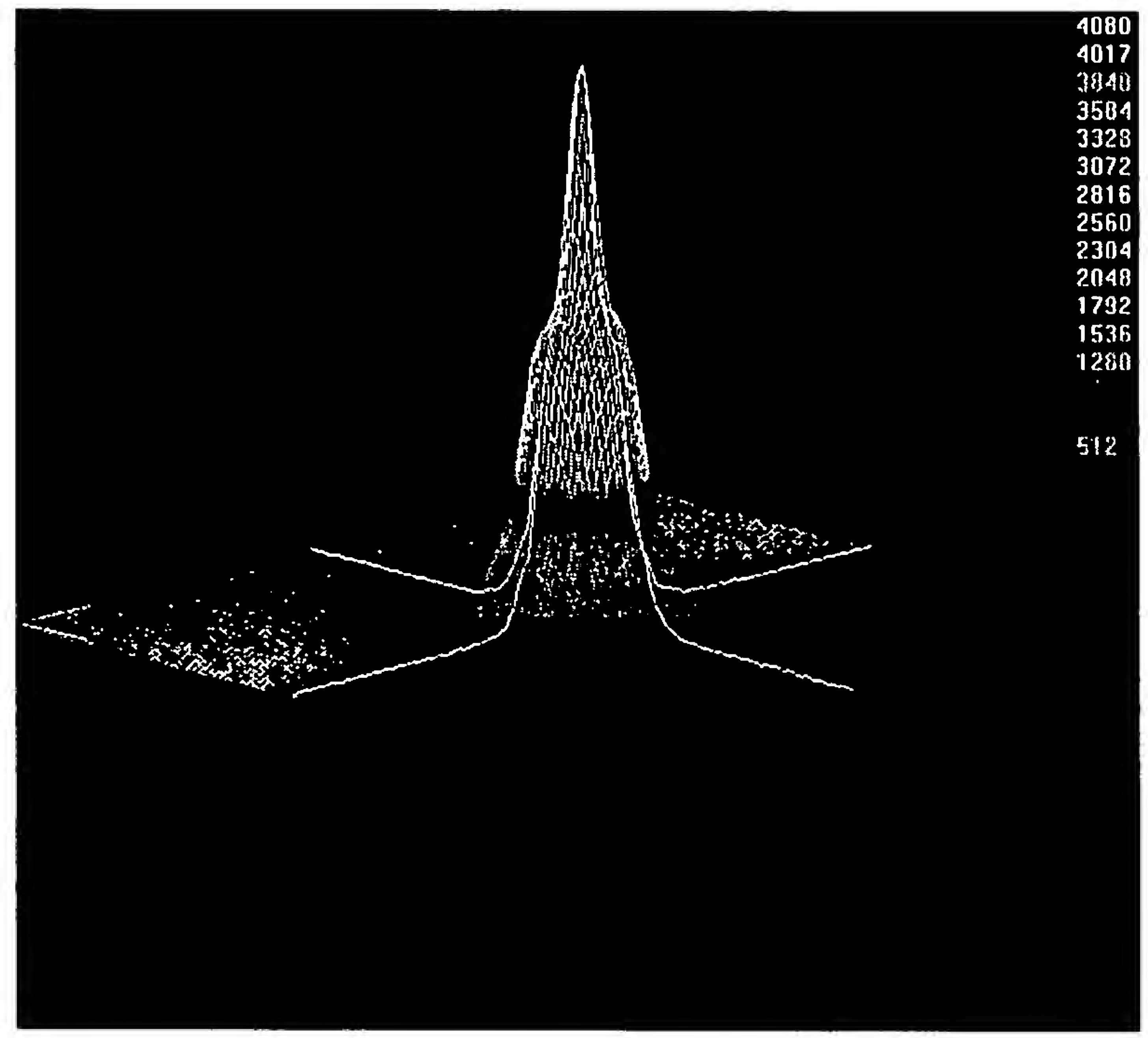
best working distance: ideal WD + 24 μm

$\Rightarrow$ additional insertion loss: < 0.05dB

# CMMF-SMF 3/4 Pitch Optic

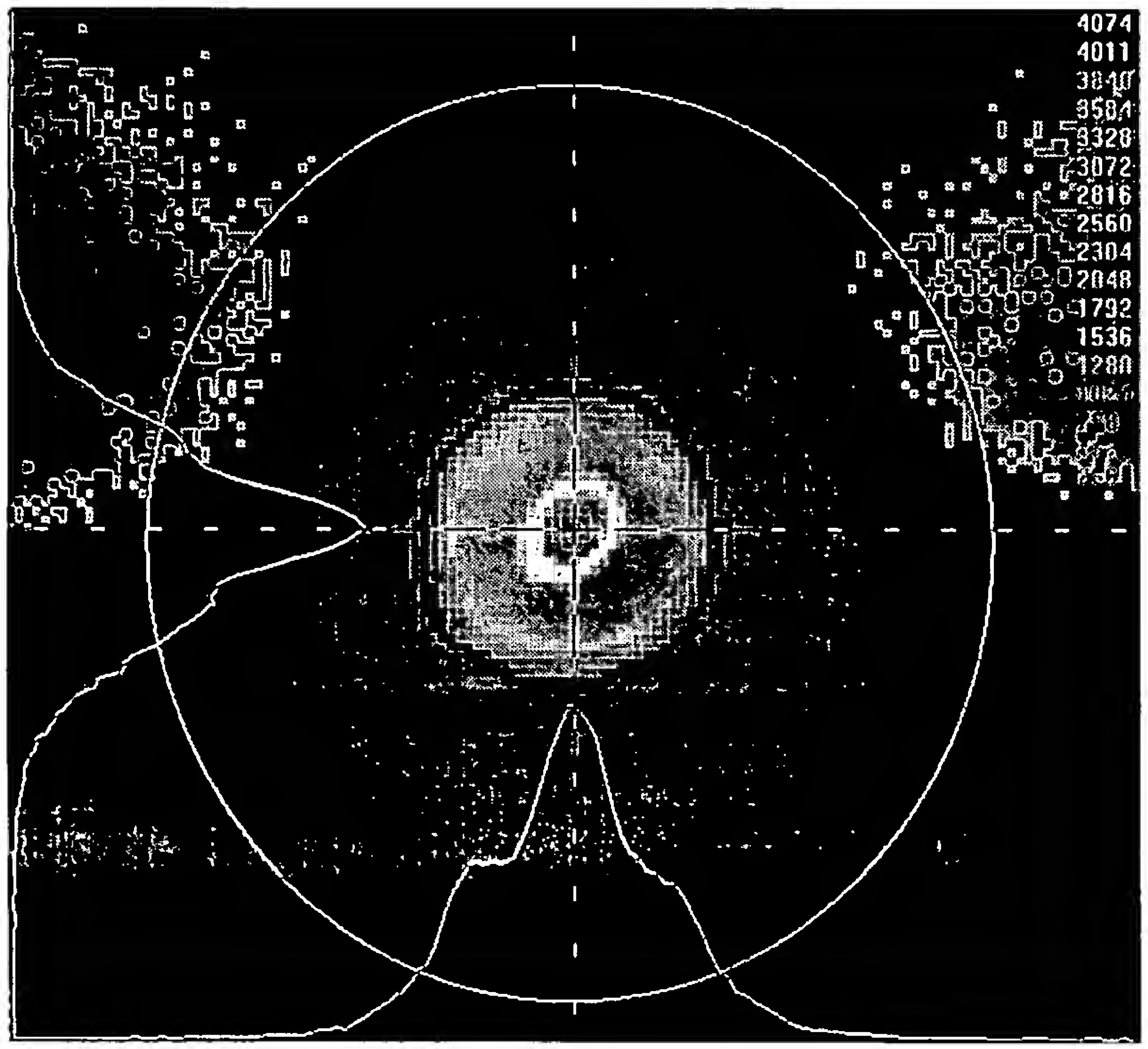
***Beam MFD at $D_1$ Spot Size = 15.39 $\mu m$ +/- 1.52 $\mu m$***

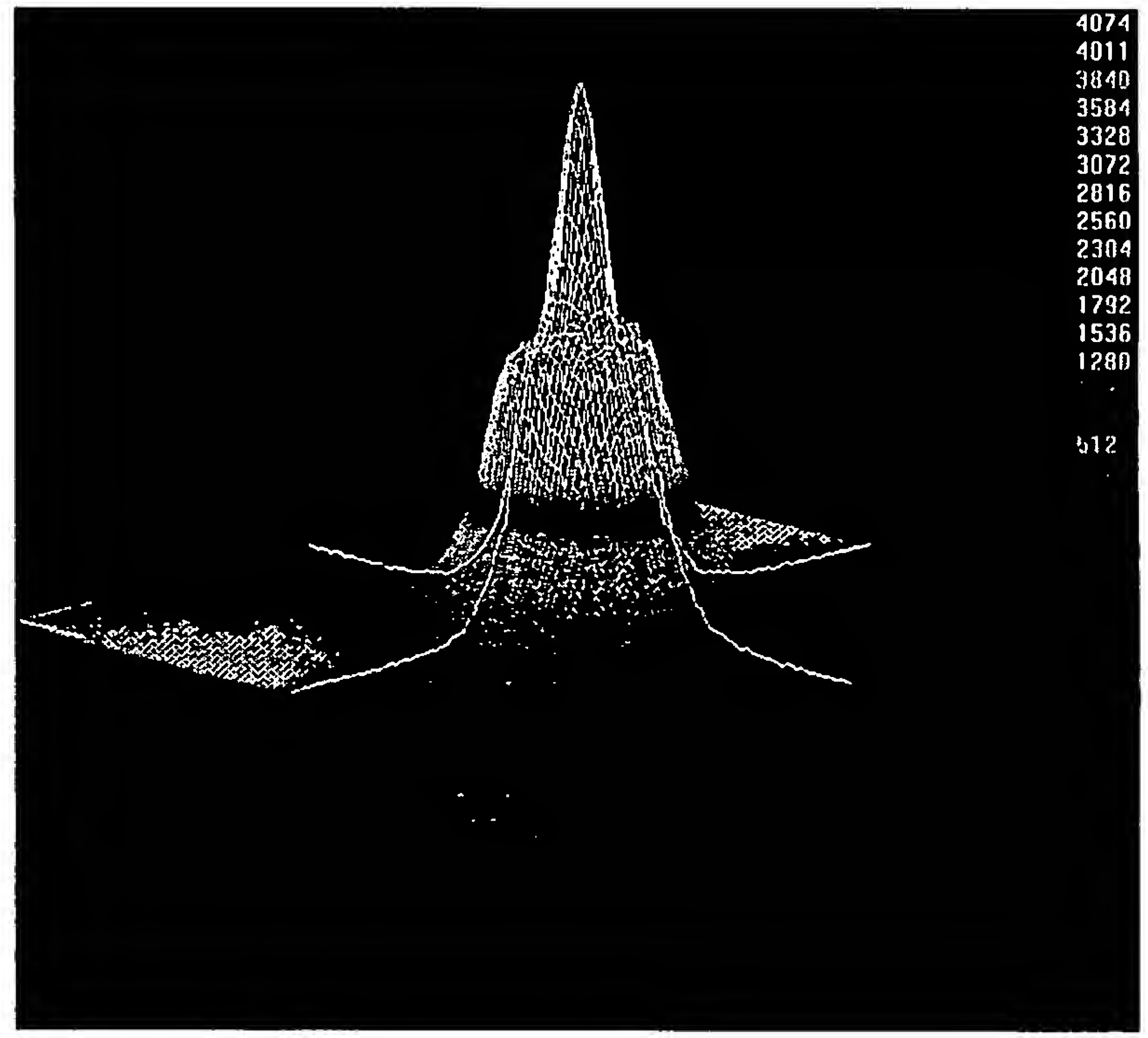


# CMMF-SMF 3/4 Pitch Optic

**Beam MFD at $D_2$ Spot Size = 15.39 $\mu m$ +/- 1.52 $\mu m$**

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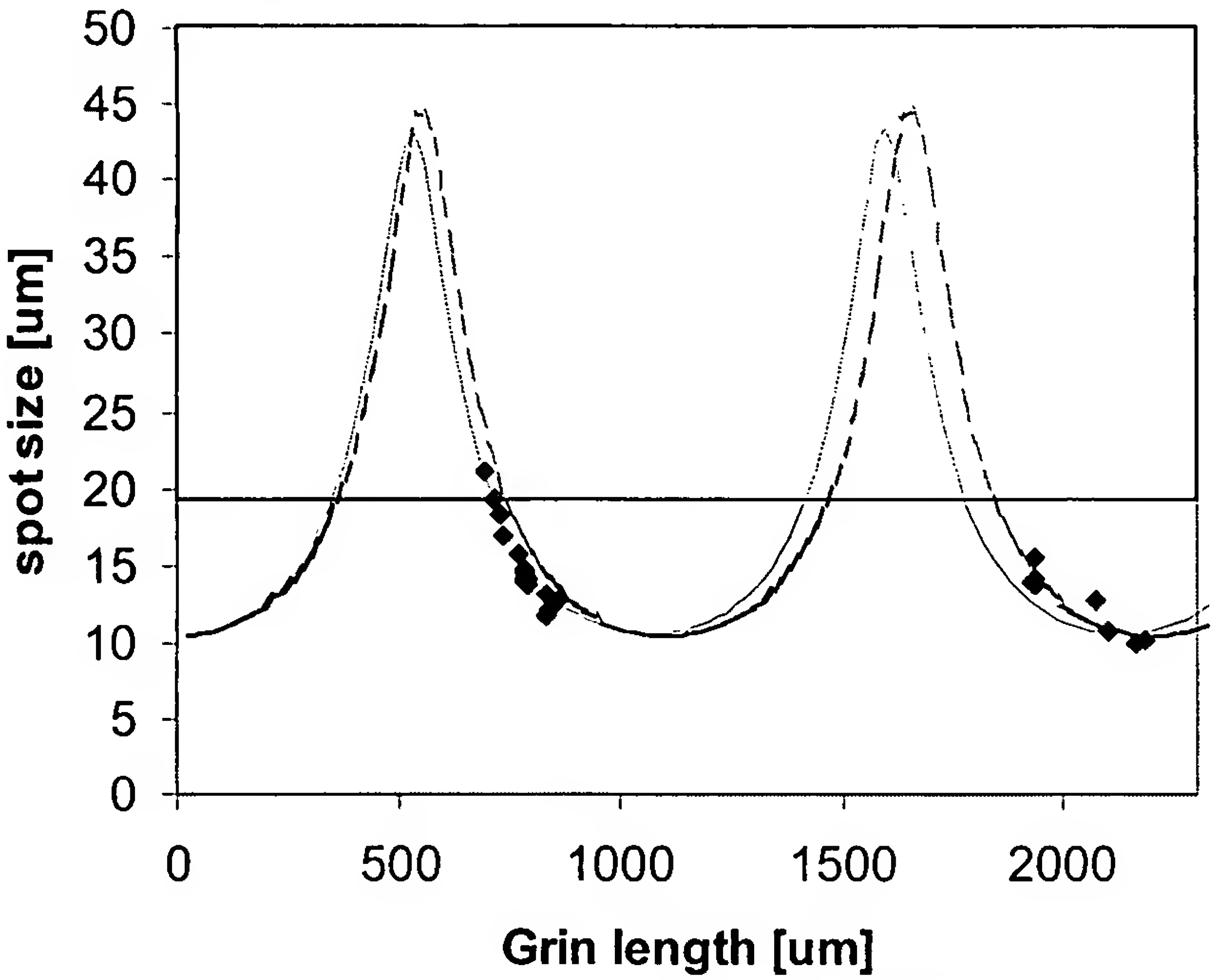
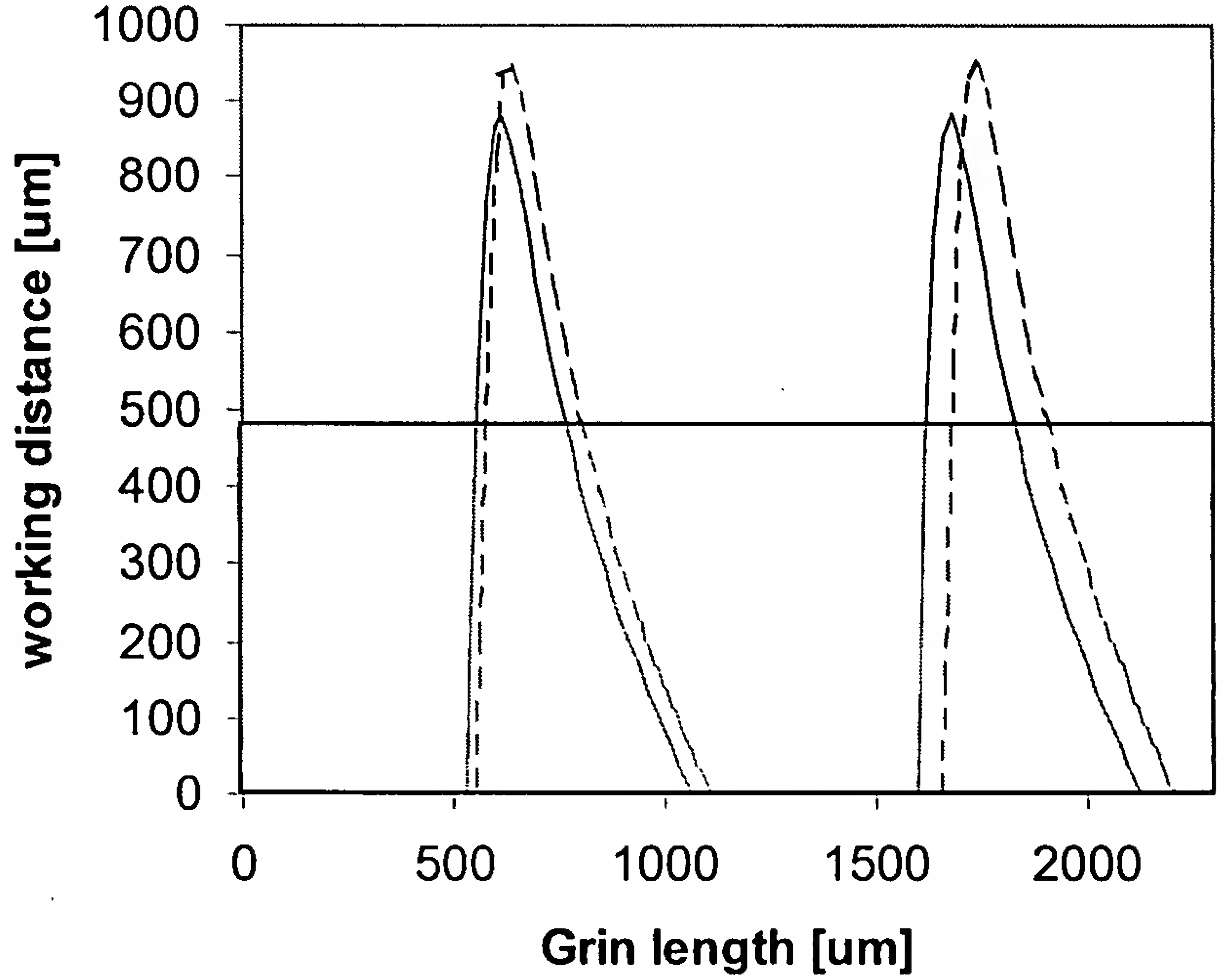
# CMMF-SMF 1/4 Pitch
# Experiment -Theory comparison




Target values:
(30 deg)

—— $g = 2.85 mm^{-1}$ $\Rightarrow$ grin length: 770um,
WD = 550um, spot size = 17.2um

—— $g = 2.95 mm^{-1}$ $\Rightarrow$ grin length: 740um,
WD = 550um, spot size = 17.4um

—— Requested
—— Delivered

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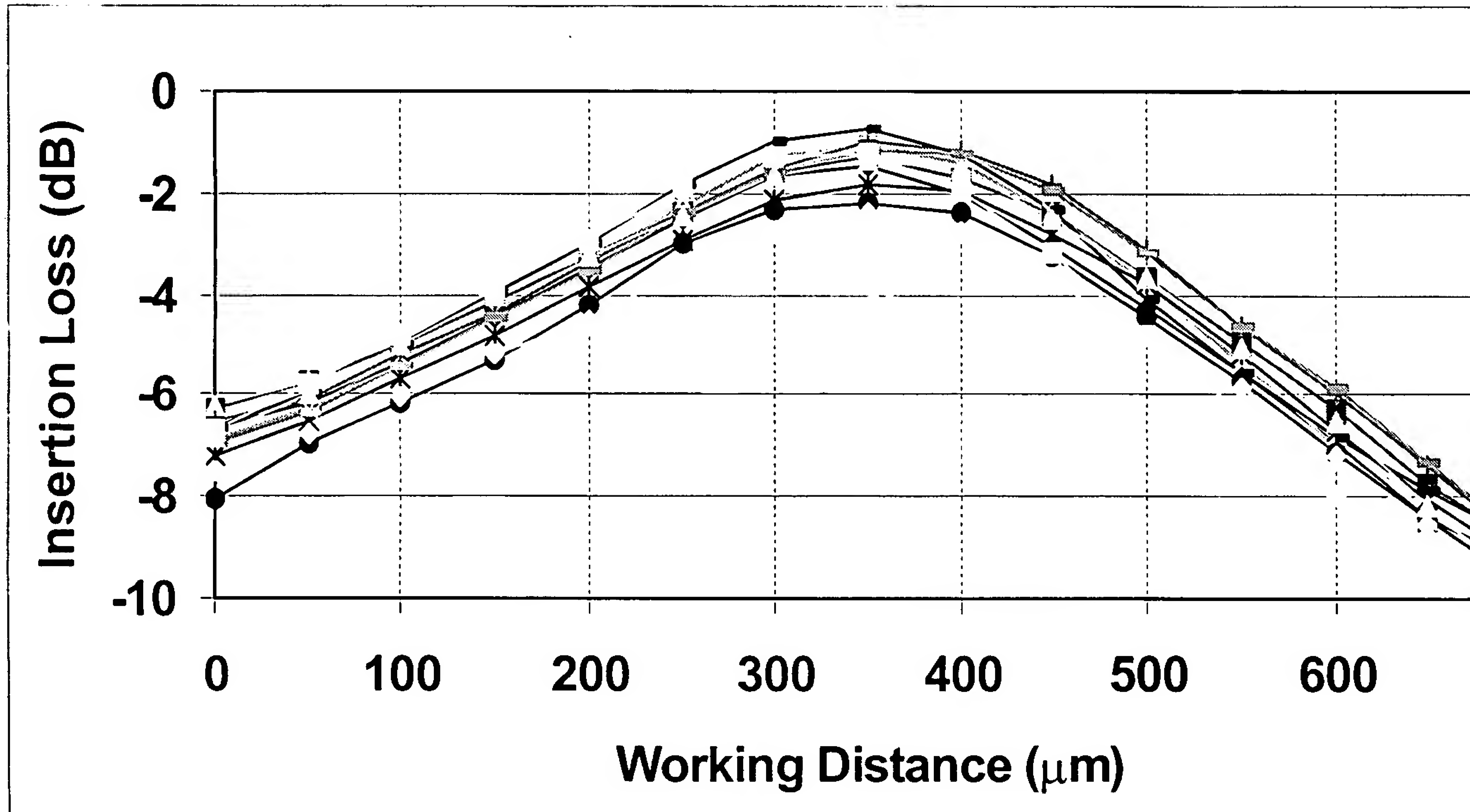
# CMMF 'Grin' Lengths

| ID | Type | GRIN Length (μm) |
|---|---|---|
| 1 | 750-C-CMMF-SMF-80 | 757.1 |
| 2 | 750-C-CMMF-SMF-80 | 760.1 |
| 3 | 750-C-CMMF-SMF-80 | 750.2 |
| 4 | 750-C-CMMF-SMF-80 | 754.0 |
| 5 | 750-C-CMMF-SMF-80 | 743.0 |
| 6 | 750-C-CMMF-SMF-80 | 749.6 |
| 7 | 750-C-CMMF-SMF-80 | 753.0 |
| 8 | 750-C-CMMF-SMF-80 | 756.5 |
| 9 | 750-C-CMMF-SMF-80 | 753.7 |
| 10 | 750-C-CMMF-SMF-80 | 755.1 |

| | GRIN length |
|---|---|
| Average: | 753.2 |
| Stdev: | 4.76 |
| Max: | 760.1 |
| Min: | 743.0 |
| Range: | 17.1 |

- Have made a few other sets with similar consistency. Many sets of optics did not exhibit the same consistency as shims were used to vary the grin length and this resulted in optics not optimized for consistent grin length.

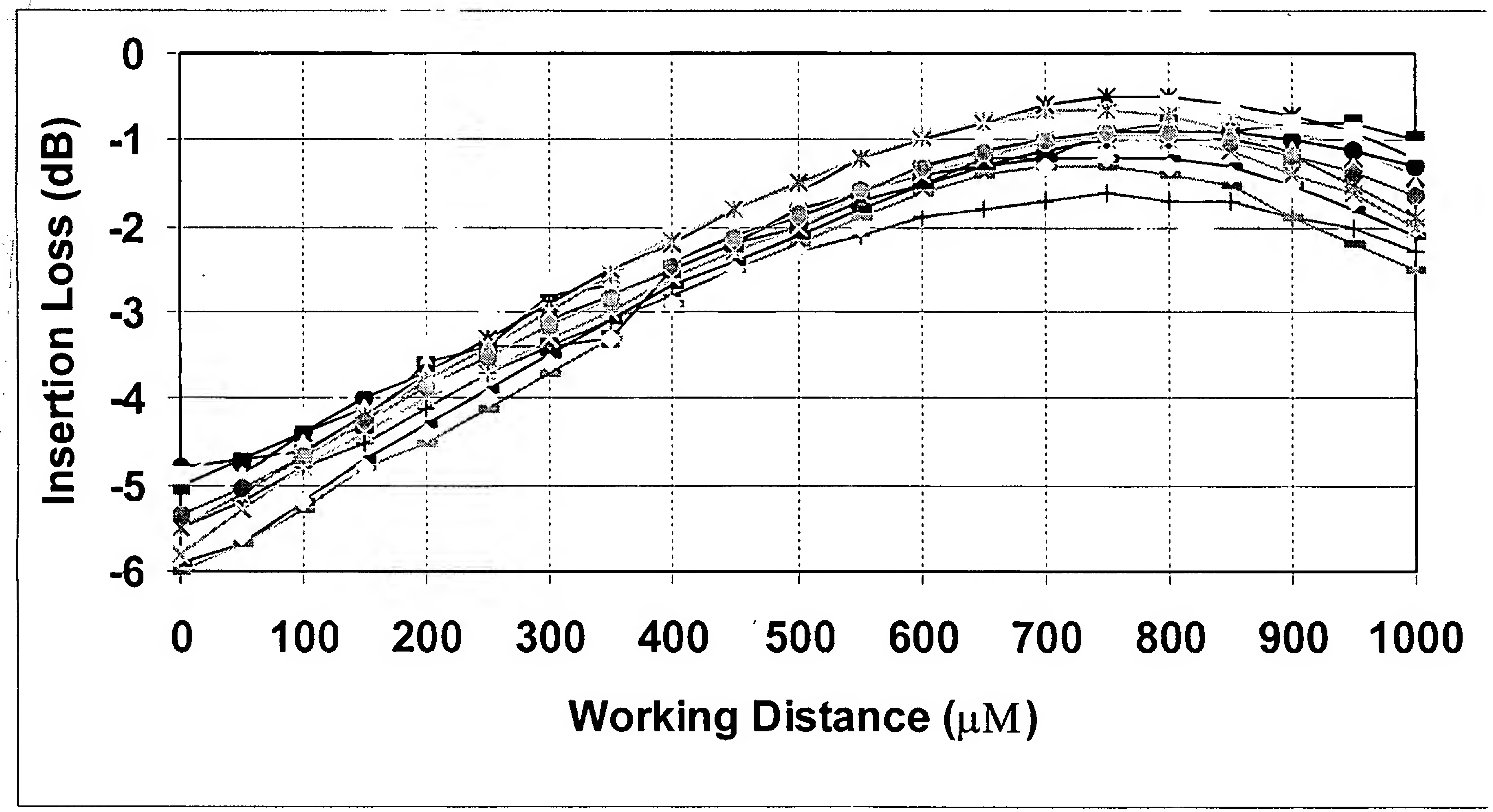
# CMMF Optical Coupling Fiber to Fiber - in V Groove




| | Peak value |
|---|---|
| | -1.48 |
| | -1.27 |
| | -1.12 |
| | -1.05 |
| | -1.84 |
| | -2.17 |
| | -1 |
| | -0.73 |
| | -1.14 |
| | -2.36 |
| | -1.23 |
| | -1.33 |
| Avg. | -1.39 |
| Stdev. | 0.49 |
| Range | 1.63 |

**850 μm 'GRIN' fiber**

# CMMF Optical Coupling Fiber to Fiber - in V Groove Con't




| | Peak value |
|---|---|
| | -1 |
| | -0.9 |
| | -0.75 |
| | -0.6 |
| | -0.5 |
| | -0.9 |
| | -1.6 |
| | -1.2 |
| | -1.3 |
| | -1.2 |
| | -0.7 |
| | -0.8 |
| | -1 |
| | -0.64 |
| Avg. | -0.94 |
| Stdev. | 0.31 |
| Range | 1.1 |

715 μm 'GRIN' fiber

# *CMMF Optical Coupling Fiber to Fiber - in Chip*

| OCLI-170B Epoxy | | Fully cured in chip |
|---|---|---|
| ID # | In-chip without adhesive | |
| C1 | n/a | -1.11 |
| B6-08 | -1.03 | -1.11 |
| B6-D12 | -0.78 | -0.68 |
| B6-G08 | -1.13 | -1.01 |
| B5-L04 | -0.82 | n/a |
| Avg. | **-0.94 dB** | **-0.98 dB** |
| Stdev. | **0.17 dB** | **0.20 dB** |
| Range | **0.35 dB** | **0.43 dB** |

- **OCLI-170B epoxy use discontinued due to low adhesion strength.**
- **Coupling loss greater then next slide due to being initial coupling work not due to epoxy.**

# *CMMF Optical Coupling Fiber to Fiber - in Chip Con't*

| OCLI-46A Epoxy | | Fully cured in chip |
|---|---|---|
| ID # | In-chip without adhesive | |
| B5-F04 | -0.62 | -0.56 |
| B6-D04 | -1.12 | -1.2 |
| B5-F08 | -0.83 | -0.79 |
| B5-C08 | -0.74 | -0.78 |
| B5-C04 | -0.77 | -0.79 |
| B5-F12 | -0.85 | -0.88 |
| B2-E15 | -0.71 | -0.98 |
| B3-J15 | -0.61 | -0.79 |
| B1-E15 | -0.59 | -0.6 |
| Avg. | **-0.76 dB** | **-0.82 dB** |
| Stdev. | **0.16 dB** | **0.19 dB** |
| Range | **0.53 dB** | **0.64 dB** |

- **OCLI-46A epoxy used due to increased adhesion strength and higher Tg.**
- **Coupling loss better then previous slide due to improved optical sub-assemblies and further chip assembly experience.**

# Temperature Dependence - CMMF Optics

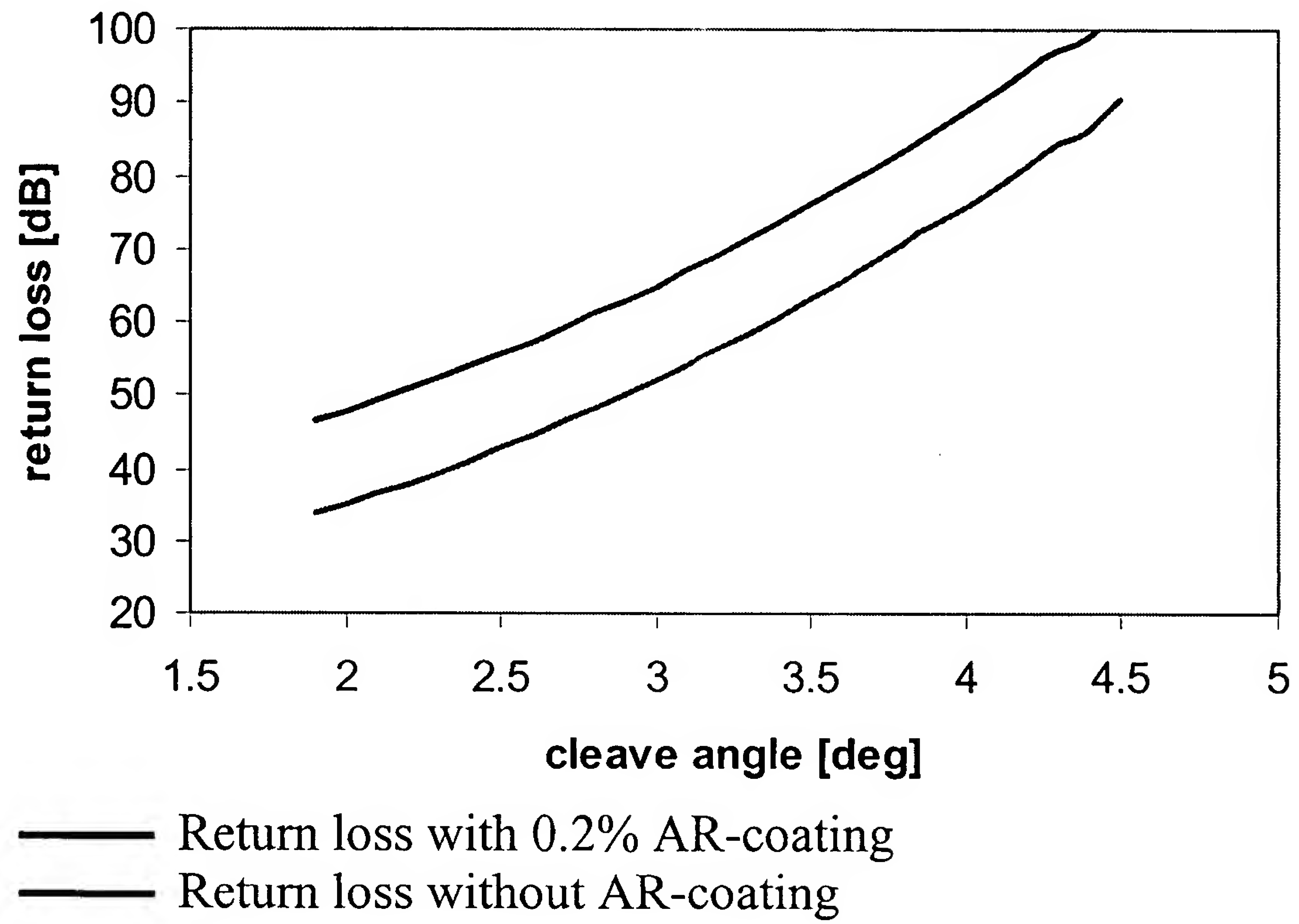
| | Delta IL over Temperature (-5°C to 70°C) | | | |
|---|---|---|---|---|
| | Cycle 1 | Cycle 2 | Cycle 3 | Cycle 4 |
| E10-E1 | 0.03 | | | |
| P20-F1 | 0.06 | | | |
| C1 | 0.49 | 0.07 | 0.08 | |
| B6-08 | 0.20 | 0.16 | 0.15 | 0.16 |
| B6-D12 | 0.09 | 0.07 | 0.08 | |
| B6-G08 | 0.11 | 0.11 | 0.13 | |
| B5-L04 | 0.11 | 0.11 | | |
| B5-F04 | 0.10 | 0.10 | 0.12 | |
| B5-F08 | 0.40 * | 0.10 | 0.05 | |
| B5-C04 | 0.90 * | | | |
| B5-F12 | 0.10 | 0.09 | | |
| B2-E15 | 0.13 | 0.12 | | |
| B3-J15 | 0.07 | | | |
| B1-E15 | 0.04 | | | |
| Avg. | **0.20 dB** | **0.10 dB** | **0.10 dB** | **0.16 dB** |
| Stdev. | **0.24 dB** | **0.03 dB** | **0.04 dB** | |
| Range | **0.87 dB** | **0.09 dB** | **0.10 dB** | |

**Overall Average** **0.15 dB**
**Overall Average w/o *** **0.11 dB**

*** believed these parts were incorrectly loaded into temperature chamber, fiber pinched in port inducing excess loss and instability**

- **In addition:**
  - **1 part build and temperature tested on bench with cure in place cartridge heater:**
    - **0.04 dB IL change amb to 150°C (cure temp)**
    - **0.01 dB IL change amb to 70°C cycling.**

# Return Loss vs. Cleave Angle




3-deg angle cleave plus AR-coating results in 65dB return loss

# Splice Return loss CMMF

| | ID | Measurement | P1 | P2 | S | C | RL |
|---|---|---|---|---|---|---|---|
| splice 1A | 1 | 56.70 | 57.90 | 1.20 | 1.96 | 59.86 | 59.52 dB |
| " | 2 | 56.60 | 58.00 | 1.40 | 1.19 | 59.19 | |
| splice 2A | 1 | 56.70 | 57.90 | 1.20 | 1.96 | 59.86 | 64.01 dB |
| " | 2 | 57.70 | 57.90 | 0.20 | 10.26 | 68.16 | |
| splice 3A | 1 | 55.30 | 57.90 | 2.60 | -2.15 | 55.75 | 55.75 dB |
| " | 2 | 55.30 | 57.90 | 2.60 | -2.15 | 55.75 | |
| splice 4A | 1 | 56.70 | 57.90 | 1.20 | 1.96 | 59.86 | 61.52 dB |
| " | 2 | 57.30 | 57.90 | 0.60 | 5.28 | 63.18 | |
| | | Average | 60.20 dB | | | | |

# *Angle Cleaving*

| ID | Type | GRIN Length (μm) | Fringes | Angle |
|---|---|---|---|---|
| 1 | 750-C-CMMF-SMF-80 | 765.5 | 24 | 3.63° |
| 2 | 750-C-CMMF-SMF-80 | 772.4 | 24 | 3.63° |
| 3 | 750-C-CMMF-SMF-80 | 756.5 | 23 | 3.48° |
| 4 | 750-C-CMMF-SMF-80 | 765.5 | 25 | 3.78° |
| 5 | 750-C-CMMF-SMF-80 | 733.9 | | |
| 6 | 750-C-CMMF-SMF-80 | 746.8 | 22 | 3.33° |
| 7 | 750-C-CMMF-SMF-80 | 760.9 | 25 | 3.78° |
| 8 | 750-C-CMMF-SMF-80 | 766.5 | 23 | 3.48° |
| 9 | 750-C-CMMF-SMF-80 | 757.5 | 25 | 3.78° |
| 10 | 750-C-CMMF-SMF-80 | 745.5 | 23 | 3.48° |
| 11 | 750-C-CMMF-SMF-80 | 759.1 | 22 | 3.33° |
| 12 | 750-C-CMMF-SMF-80 | 757.5 | 23 | 3.48° |
| | **Average:** | **757.3** | 23.5 | **3.56°** |
| | **Stdev:** | **10.71** | 1.13 | **0.17°** |
| | **Max:** | **772.4** | 25.0 | **3.78°** |
| | **Min:** | **733.9** | 22.0 | **3.33°** |
| | **Range:** | **38.5** | 3.0 | **0.45°** |

- **Angle ≠3.0° because 1 fringe = 0.151° rather then previously believed 0.125°**
- **New target fringe count = 20**
- **GRIN length inconsistency due to shims used to achieve ~760μm length**

# Optics Reversibility

| | | Signal | Signal | |
|---|---|---|---|---|
| **PART #** | **Chip ID** | **Input/Output (dB)** | **Output/Input (dB)** | **Delta** |
| 1 | C1 | -1.12 | -1.09 | -0.03 |
| 2 | B5_L04 | -0.83 | -0.85 | 0.02 |
| 3 | B3_J15 | -0.79 | -0.77 | -0.02 |
| 4 | B2_E15 | -1.05 | -1.04 | -0.01 |
| 5 | B5_F12 | -0.92 | -0.93 | 0.01 |
| 6 | B5_F04 | -0.64 | -0.62 | -0.02 |
| 7 | B1_E15 | -0.6 | -0.63 | 0.03 |
| 8 | B6_G08 | -0.91 | -0.93 | 0.02 |
| | **Avg.** | -0.86 | -0.86 | **0.00** |
| | **Stdev.** | 0.18 | 0.17 | **0.02** |
| | **Range** | 0.52 | 0.47 | **0.06** |

- **Tests indicate that there is not a issue related to the reversibility of the optical sub-assembly**
- **Overall loss number too high, later data indicates better and more consistent coupling.**

# *PDL in transmission, with index matching fluid to reduce etalon effects*

| Test ID | W.D. | I.L. | P.D.L. |
|---|---|---|---|
| 1 | ~ 615 | 1.64 | 0.02 |
| 2 | ~ 750 | 1.40 | 0.02 |
| 3 | ~ 900 | 0.57 | 0.03 |
| 4 | ~ 900 | 0.46 | 0.02 |
| 5 | ~ 650 | 0.69 | 0.02 |
| 6 | ~ 750 | 0.66 | 0.03 |
| 7 | ~ 650 | 0.61 | 0.02 |
| 8 | ~ 650 | 0.49 | 0.04 |
| | **Avg.** | **0.82 dB** | **0.02 dB** |
| | **Stdev.** | **0.45 dB** | **0.01 dB** |

- **PDL of optical sub-assembly appears to not be an issue.**
  - **Need to verify with actual AR coated parts.**
- **PDL effects due to optical bonding to chip unknown at this time, as well as PDL off the mirror.**

# Engineering Tests Optics

| Engineering Tests - Mems - Optics | | | | | |
|---|---|---|---|---|---|
| | | | | | |
| | Index | | | | |
| | | | | | |
| | | | | | |
| Test# | Date | | | | |
| Number: | Started: | Title: | By: | status | Key word 1 |
| | | | | | |
| 1 | 30-May-00 | IMT 2x2 Optical Power Variation over Temperature | TO | Complete | Insertion Loss |
| 2 | 6-Jun-00 | Repeat IMT 2x2 Optical Power Variation over Temperature | TO | Complete | |
| 3 | 12-Jun-00 | IMT 2x2 Optical Power Variation over Temperature (6 Neuschatel switches) | TO | Complete | |
| 4 | 13-Jul-00 | Gradissimo Fiber diameters and lengths using Wyco (Working distance = 600 um) | LB | Complete | Gradissimo |
| 5 | 18-Jul-00 | Gradissimo Fiber diameters and lengths using Wyco (Working distance = 800 um) | LB | Complete | Gradissimo |
| 6 | 18-Jul-00 | Return Loss of Single Mode to Multi Mode Splice | LB | Complete | Return Loss |
| 7 | 6-Jun-00 | IMT Nueschatel Asemblied 2x2 Insertion Loss | LB | Complete | Insertion Loss |
| 79 | 24-Oct-00 | Grin Length Study, Tension Setting of Tension Cleaver | JC, LB | writing up | Grin Length |
| 80 | 25-Oct-00 | Insertion Loss over Temperature using CMMF (*C1.0 program*) | DM | Complete | Temperature |
| 81 | 6-Nov-00 | Transmission study, consistency of signal for input and output | DM | Complete | Transmission |
| 82 | 7-Nov-00 | Insertion Loss over Temperature using CMMF (*C1.2 program*) | DM | In Process | Temperature |

# Insertion Loss vs. Wavelength Assumptions

- mode field radius $w_0$ of SMF given by:

$$w_0(\lambda) = a \cdot \left(0.65 + \frac{1.619}{V^{1.5}} + \frac{2.879}{V^6}\right)$$

$$V(\lambda) = \frac{2\pi}{\lambda} a \cdot NA$$

with a = 4.1μm, SMF-28 core radius;
NA = 0.12, SMF-28 numerical aperture

- dispersion of on axis refractive index $n_0$:

$$n_0(\lambda) = C_0 + C_1\lambda$$

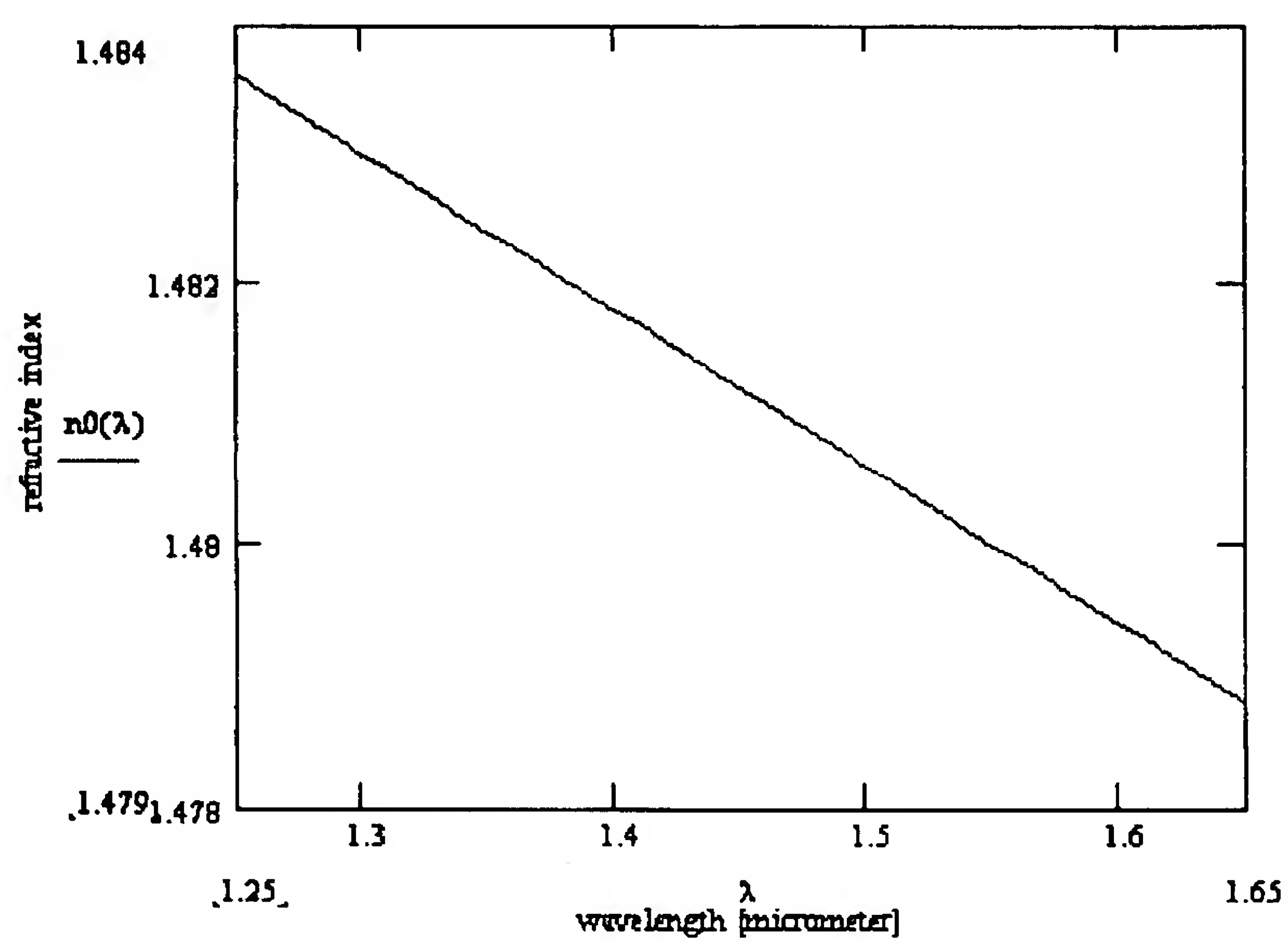
- dispersion of Grin parameter g:

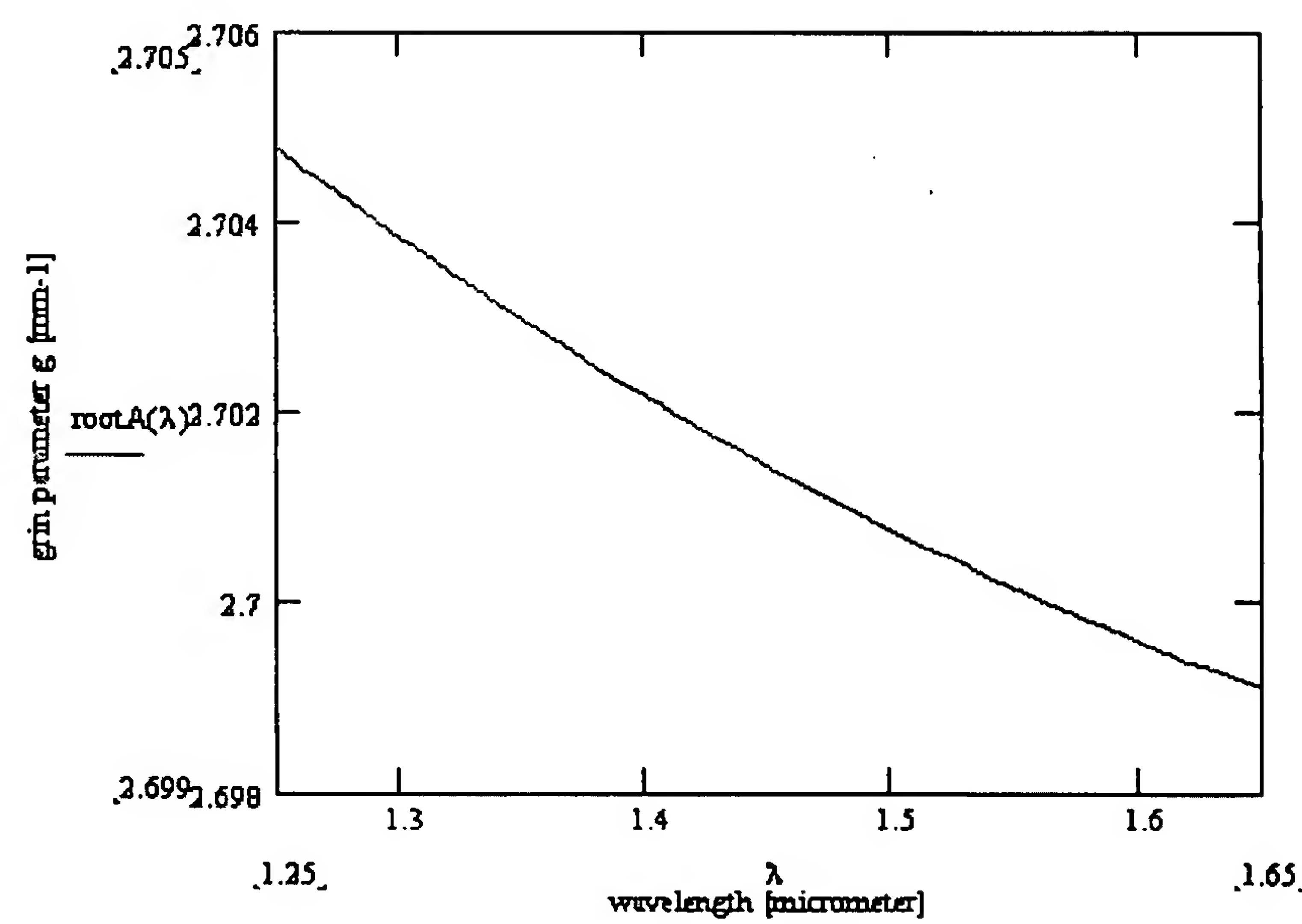
$$g(\lambda) = \sqrt{-2 \cdot \frac{D_0 + D_1\lambda + D_2\lambda^2}{n_0(\lambda)}}$$

This model does not take into account any AR-coating or absorption.

# Insertion Loss vs. Wavelength Parameters

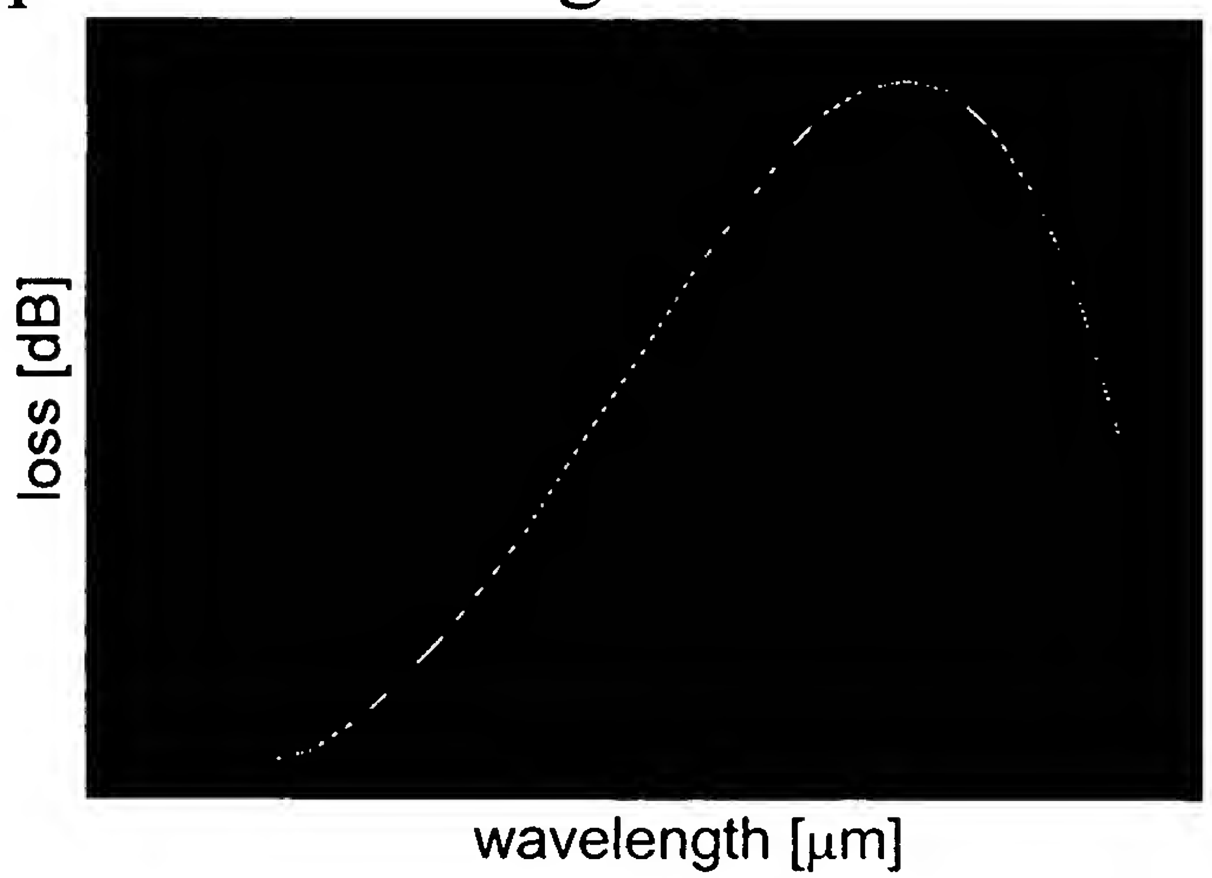
Wavelength range: 1250 - 1650 nm
Mode field diameter: 8.85 - 11.05 µm, $2w_0(1310) = 9.13$ µm, $2w_0(1550) = 10.42$ µm
On-axis refractive index $n_0$: 1.4836 - 1.4788, $n_0(1.55) = 1.48$
Grin parameter g (≡rootA): 2.705 - 2.699 $mm^{-1}$, $g(1.55) = 2.7\ mm^{-1}$



# Insertion Loss vs. Wavelength Results

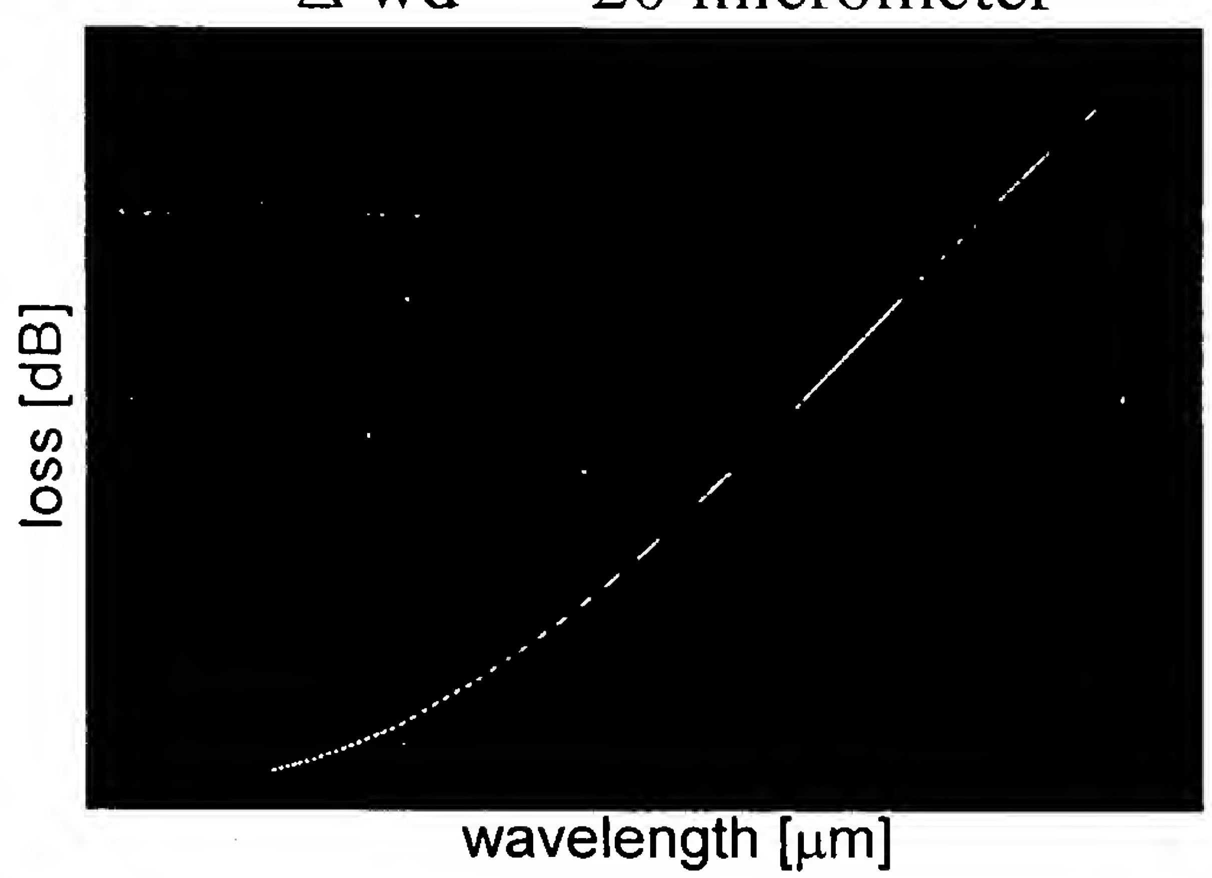
Optimum working distance for $\lambda$=1.55μm



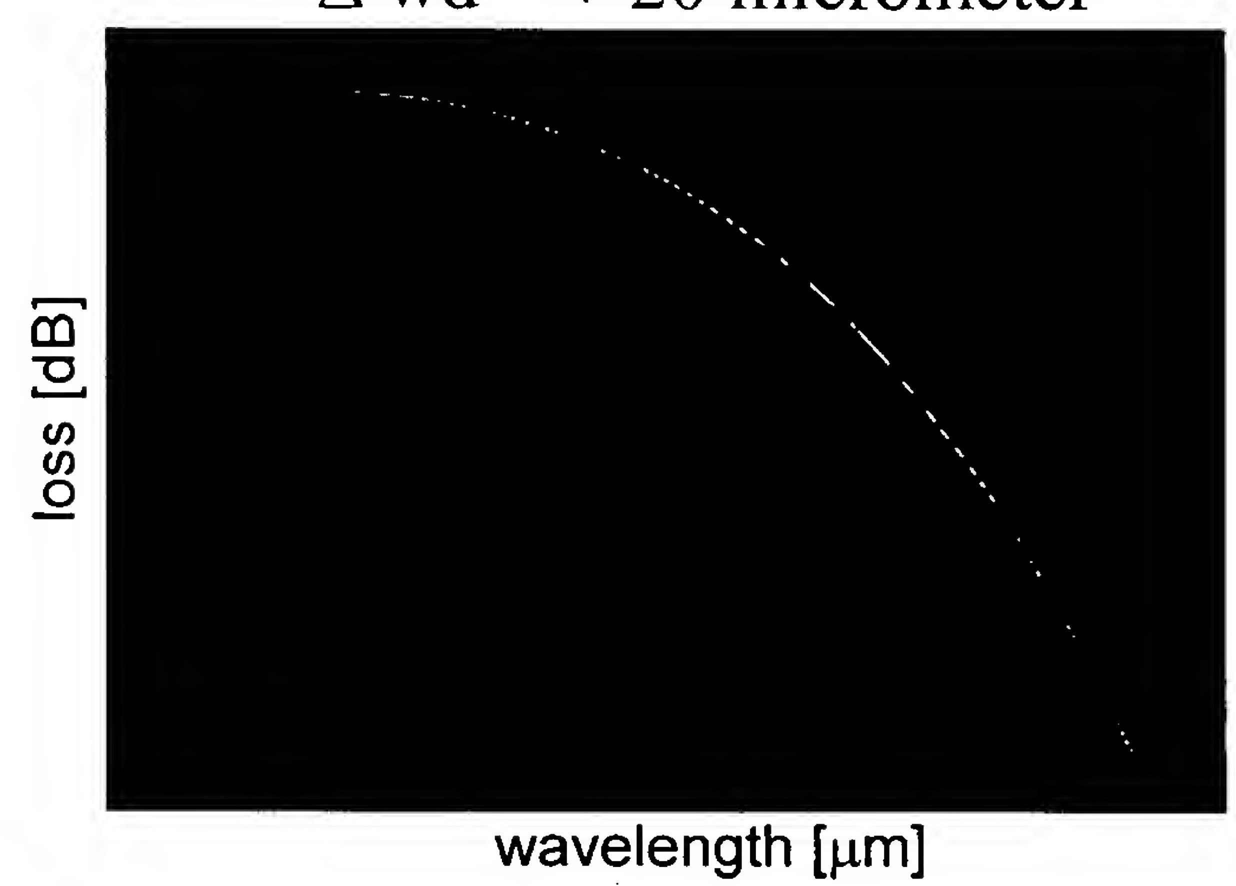

Maximum insertion loss change over 1250 - 1650nm wavelength range: $\Delta IL < 0.005dB$

Flatness highly dependent on misalignments (as seen in the two figures below).

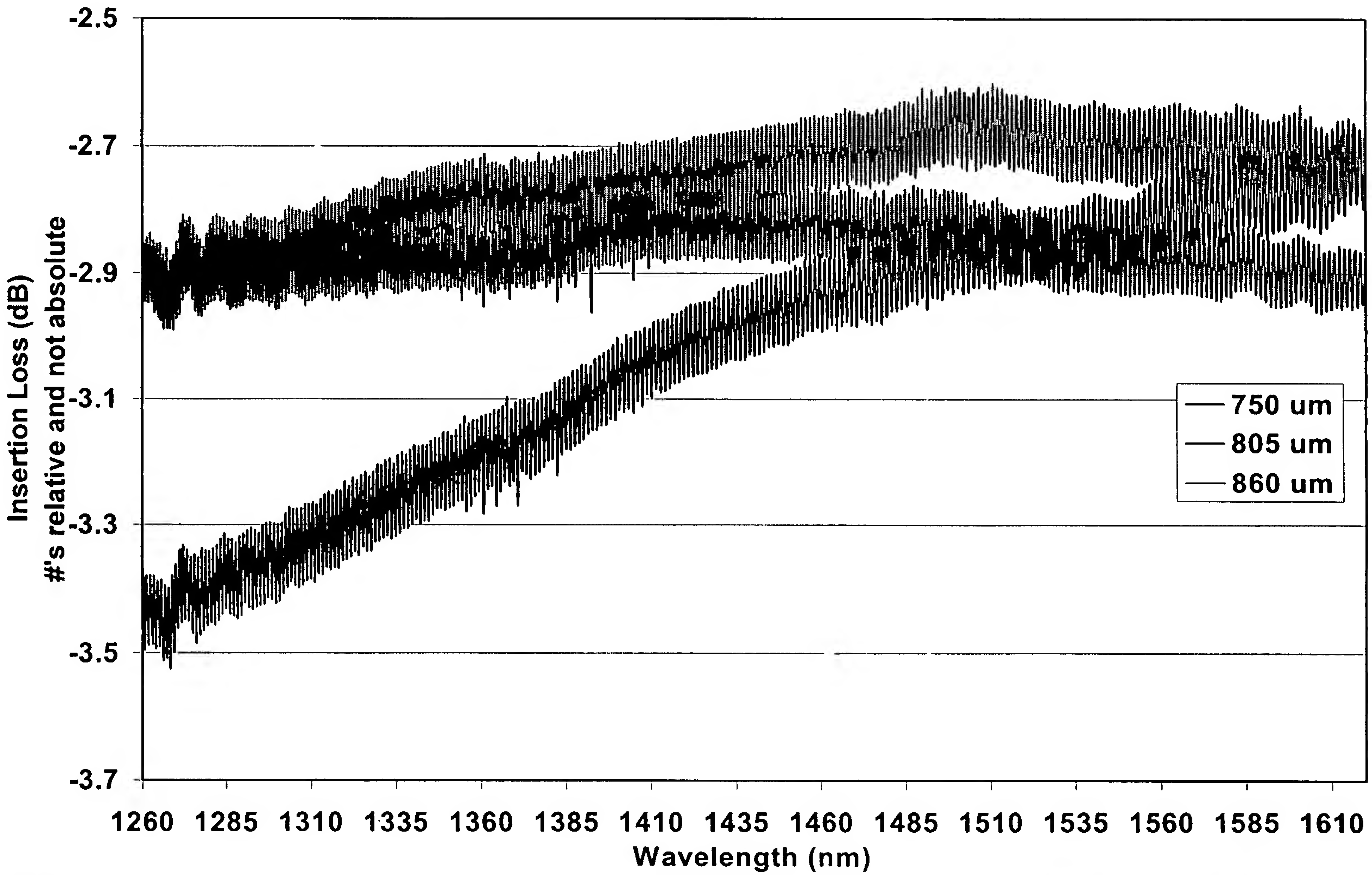
$\Delta$ wd = - 20 micrometer




$\Delta$ wd = + 20 micrometer



# Actual Wavelength Dependence

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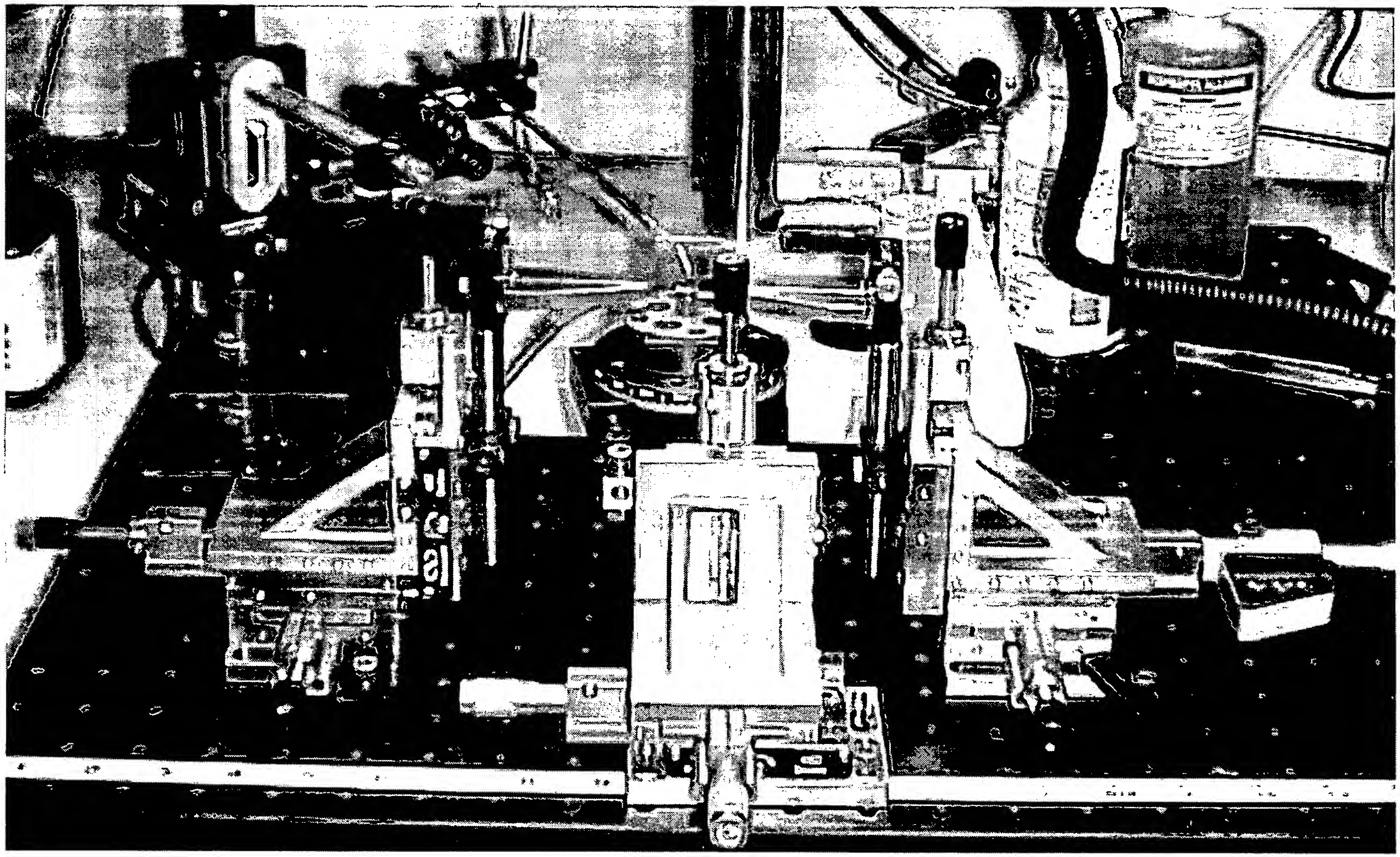
# MEMS Optical-Chip Assembly

## Current Process

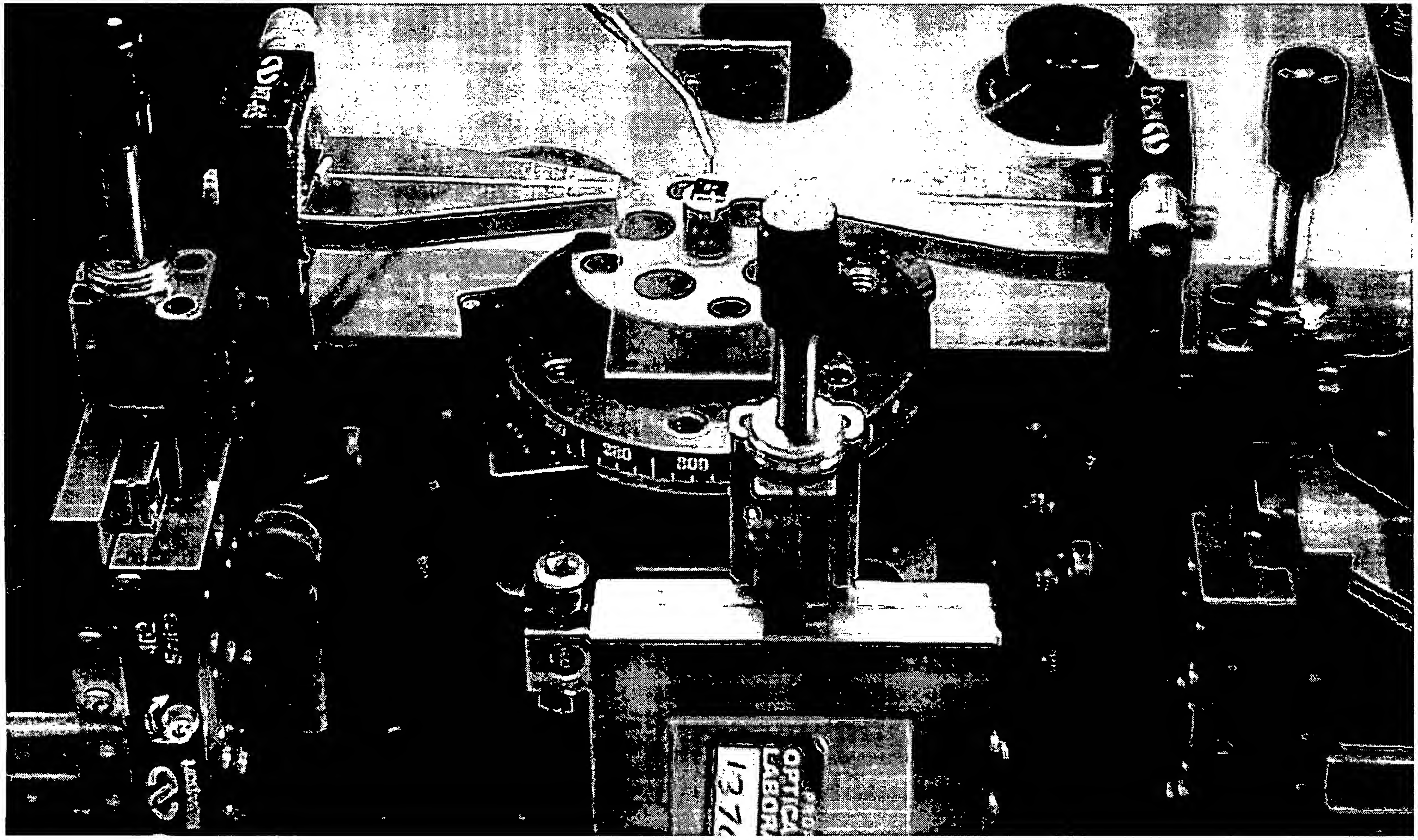
# Current Optical Assembly Process

- Align fibers in transmission in fiber trenches, without epoxy.
- Record optimum alignment insertion loss.
- Remove fibers and apply epoxy
  - Epoxy transfer from glass slide to fiber.
- Align fibers
- UV tack
- Transfer to oven for 150°C cure for 1/2 hour.
  - Parts for cure in place cartridge heater being made.

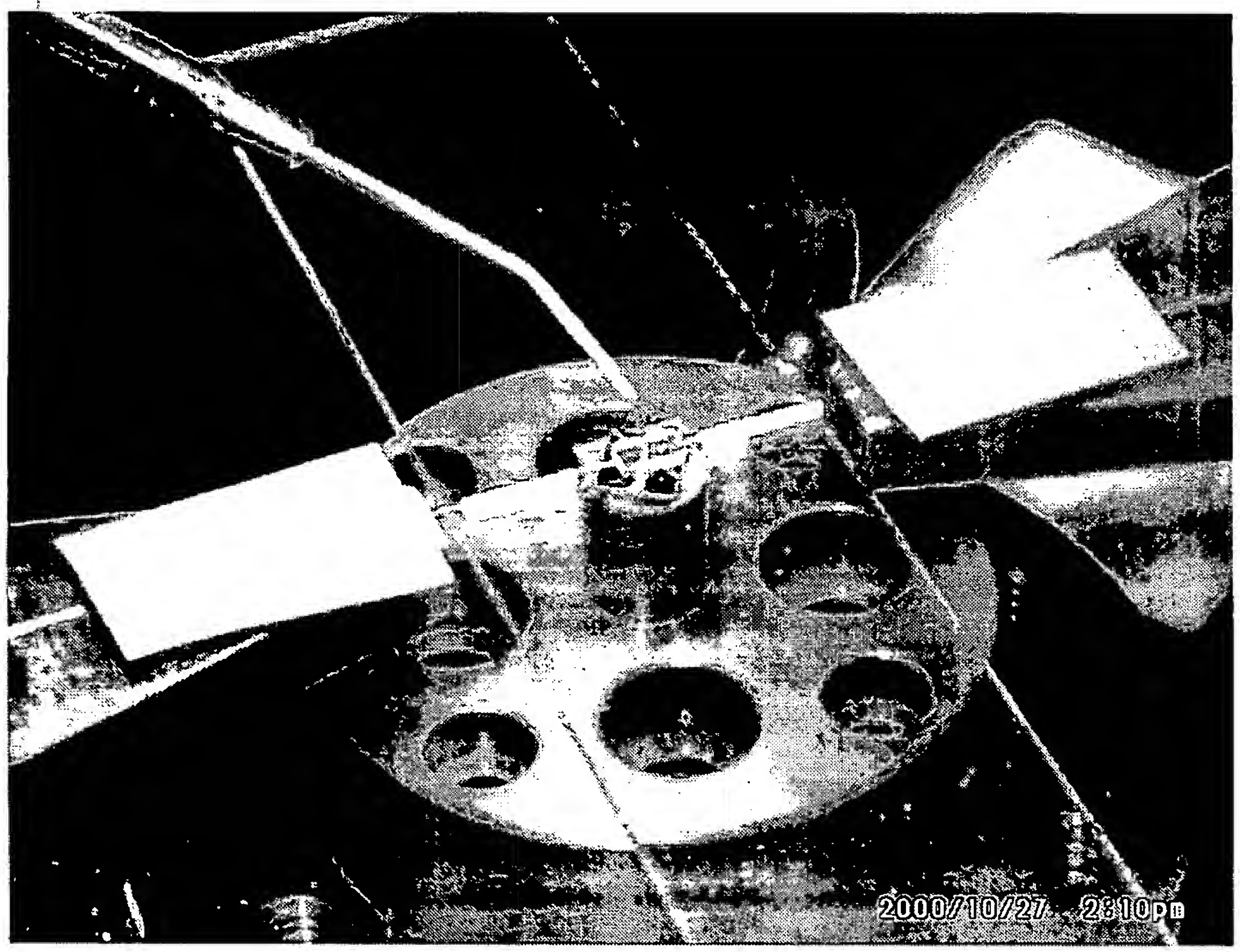
# Current Optical Assembly pictures

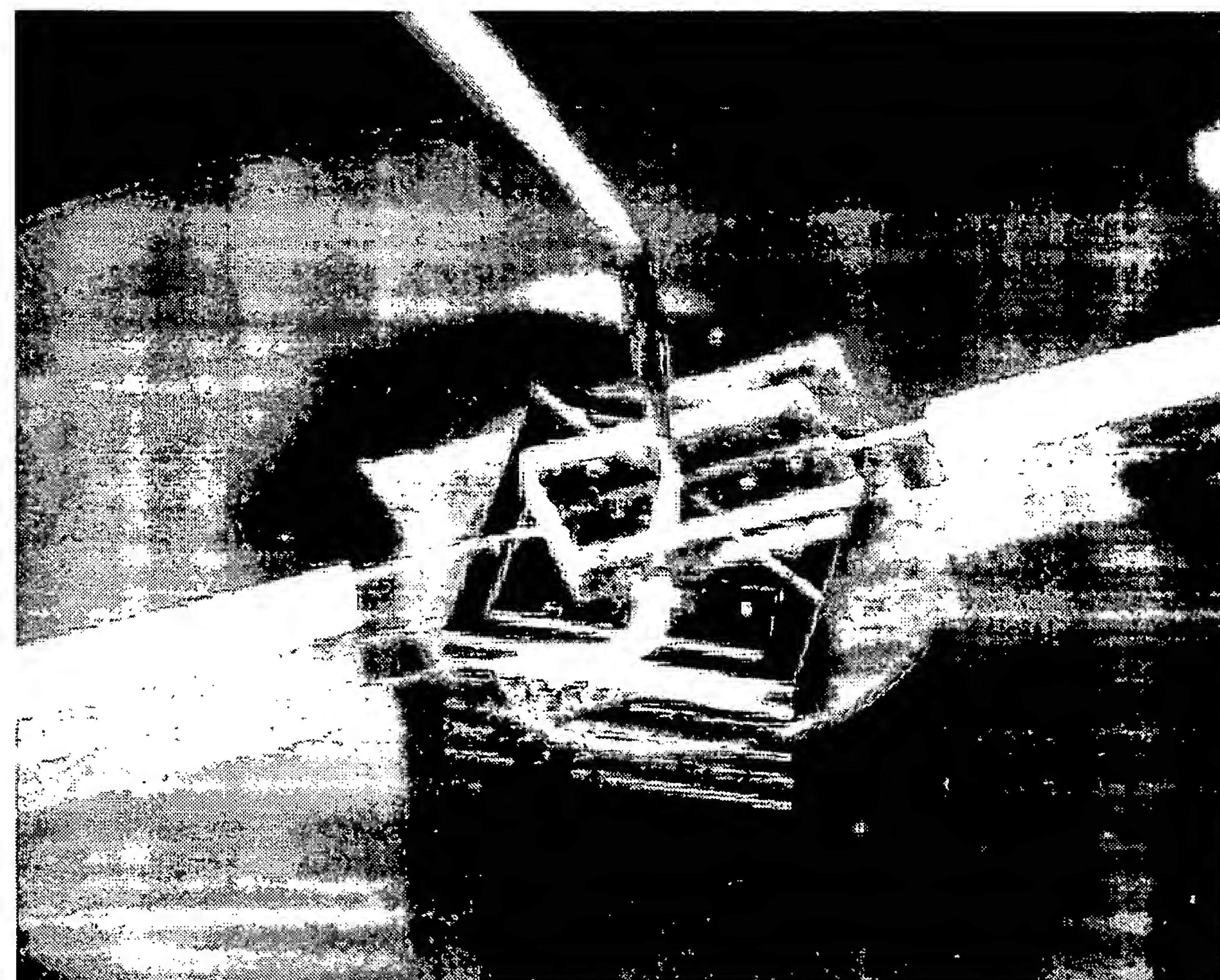


# Current Optical Assembly pictures con't



# Current Optical Assembly pictures con't



# *Cycle Times - Optical Assembly*

- 10 minutes for set of optics in transmission
  - Includes baselining equipment, splicing in optics, aligning in chip w/o and w/ epoxy, & UV cure.
  - Angle cleaved optics will likely have negligible effects on cycle time as current optics are rotationally aligned.
- 1x2 and 2x2 switches will result in 2-3 time increase in cycle time.
  - Estimated cycle time for actual switch ~ 30 minutes.